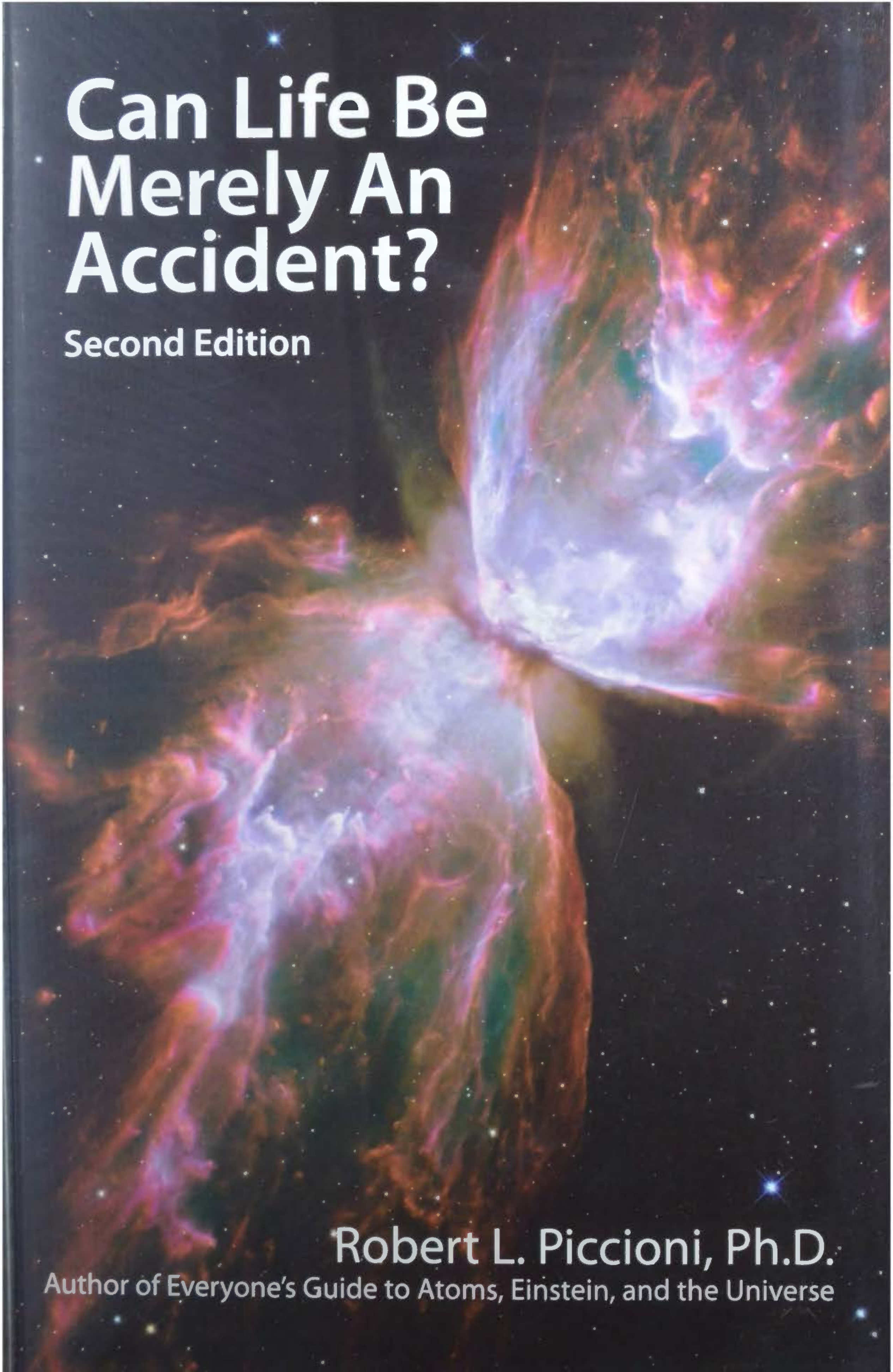
Can Life Be Merely An Accident?

Second Edition



Robert L. Piccioni, Ph.D.

Author of Everyone's Guide to Atoms, Einstein, and the Universe

Can Life Be Merely an Accident?

What are the odds of :

- ***a viable universe?***
- ***the right atoms?***
- ***an Earth-like habitat?***
- ***the right genetic code?***

Read this book, then You decide.

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$17.75

ISBN: 978-0-9822780-2-4

Robert Piccioni

Front cover: Image of the Butterfly Nebula taken by NASA's newly repaired and enhanced Hubble Space Telescope. Gas ejected from a dying star creates this beautiful vista as it infuses the cosmos with carbon, oxygen, and other atoms essential to life. The Butterfly Nebula is 24,000 trillion miles (4000 light-years) away.

Back cover: Remains of the brightest supernova ever seen—brighter than Venus when first observed in 1006 A.D.—now span 360 trillion miles (60 light-years) and lie 42,000 trillion miles (7000 light-years) away. This is a composite of images from three telescopes: an x-ray image by NASA Chandra (blue), an optical image by the University of Michigan/NSF (yellow), and a radio image by NRAO VLA/GBT (red).

"Best General Science
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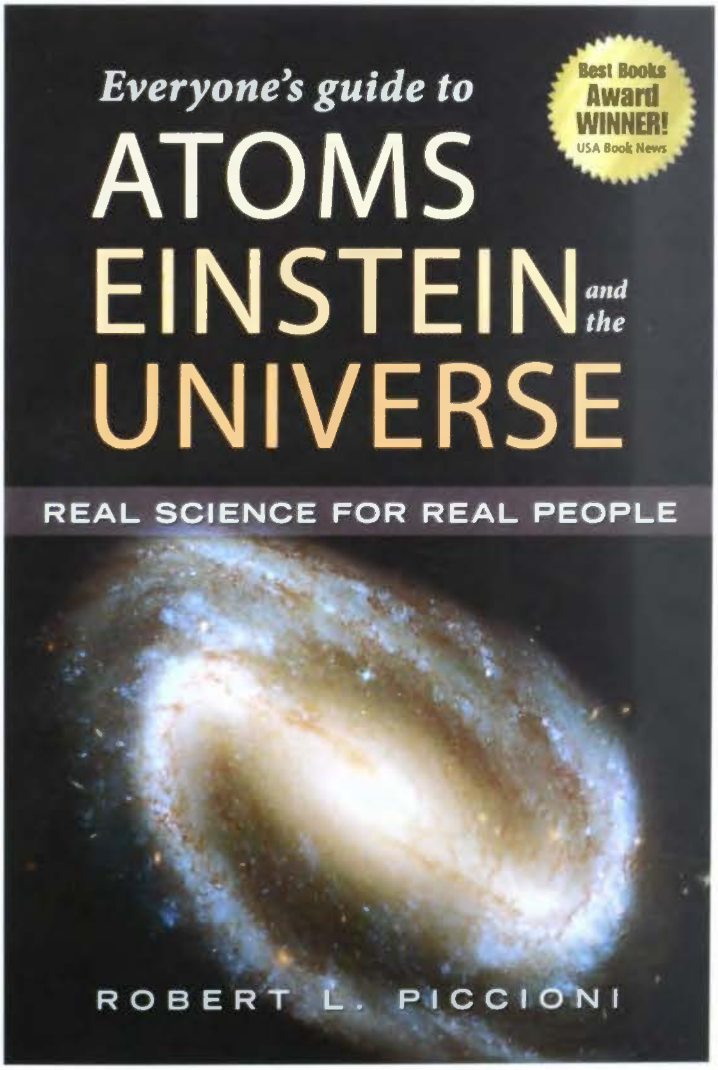
USA Book News



Praise for Dr. Piccioni's first book

Everyone's Guide to Atoms, Einstein, and the Universe

Real Science for Real People

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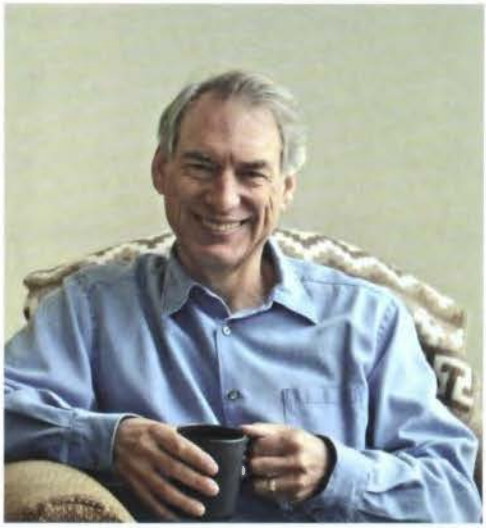

Dr. Robert Piccioni is an author, physicist, science educator, and internet radio talk show host. He explains the wonders of science at high schools, universities, churches, civic and business groups, adult education programs, and on cruise ships.

Robert has a B.S. degree from Caltech, a Ph.D. degree in high-energy physics from Stanford University, and was a research faculty member at Harvard University.

He has several patents in smart energy, medical devices, and semiconductor technologies.

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Can Life Be Merely An Accident?

by

Robert L. Piccioni, Ph.D.

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Overview

As a scientist and science educator, I strive to make the exciting discoveries of science accessible to everyone. I present Real Science, without "dumbing" anything down, in a way that is understandable for Real People—non-experts including those who fear physics or are allergic to math. In this book I present what modern science has learned about the many conditions that are necessary for the existence of any form of life, and how likely it is that those conditions could occur accidentally. We will discover that life's requirements are extremely demanding and that their occurrence by random chance is extraordinarily unlikely.

For the last 50 years or more, the common wisdom in science has been that life did indeed begin by accident, when the right molecules bumped into one another in the right way and happened to form the first DNA, the essence of life, or perhaps its simpler cousin RNA. That view was articulated by George Wald, Nobel Laureate and professor of biology at Harvard University, who said of the origin of life: "However improbable...given enough time, it will certainly happen...The time with which we have to deal is of the order of two billion years...Given so much time the 'impossible' becomes possible, the possible probable, and the probable virtually certain. One only has to wait: time itself performs the miracles."

While the substantial majority of scientists agrees with Wald's main theme, there are notable exceptions, among them Sir Fred Hoyle and Francis Crick.

Hoyle, the famous British physicist and cosmologist who coined the term "Big Bang", discovered how stars produce carbon atoms, a critical step in the development of life that we will discuss later. Hoyle said that life arising through random chemical reactions was "as likely as the assemblage of a 747 by a tornado whirling through a junkyard."

Crick, who received the Nobel Prize for discovering the structure of DNA, had little confidence in science's common wisdom about the origin of life on Earth. He said that serious consideration should be given to other alternatives "given the weakness of all theories of terrestrial genesis."

We now know that life arose on Earth, not during Wald's expanse of two billion years, but rather within no more than 600 million years after the surface cooled below water's boiling point. But, the real issue is not whether it was two billion

years or 600 million years. As we will discover in this book, the actual time that would be required for life to arise by random chance through any known physical or chemical process is far greater than millions of years, or billions of years, or even trillions of years. In fact, there is no English word, no "-illion", that does justice to such a vast expanse of time. Perhaps the closest word we have to describe Wald's "so much time" might be "infinity."

This book will not answer the question "Was life created by God or by a random accident?" I leave that to the readers to answer for themselves. I do so for two reasons. Firstly, I believe everyone is entitled to and capable of deciding this question on their own. Secondly, this is a science book and science cannot answer that question. Science has not "proven" that God exists or that He does not exist, and I believe it cannot prove either because that is beyond the realm of science. Look to science to learn the distance to the Sun, the age of the Earth, and the age of the universe. But science cannot measure or compute the purpose of life or the moral principles that should guide our lives. I believe religion and science are compatible—both are sincere efforts to seek TRUTH, something we should all value.

My views are not shared by everyone. Some believe that science and religion are irreconcilable. Some religious people believe that science is an attack on God and their faith. Some scientists believe that religion is an obstacle to enlightenment and progress. Extremists on all sides are creating a problem that need not exist. Let us evolve and live in harmony. We are all one family, everyone's DNA is 99.9% the same as everyone else's, and we are all sailing on a vast ocean, together in one small boat—planet Earth. No one has a monopoly on TRUTH; we can all benefit from each other, and should not only tolerate one another's views but also learn to find value in them.

The question then is: "Can life be merely an accident?"

Let's consider various aspects of this question:

What are atoms and which atoms does life require?
What are stars and how do they make life possible?
What is the role of galaxies and the universe?
What is special about Earth that enables it to support life?
What is DNA and what is its role in making life possible?

We will explore each topic and discover the many requirements for the existence of life. In the last chapter we will estimate the odds of these requirements being satisfied by random chance, and endeavor to arrive at an overall estimate of the odds that life could have arisen merely by accident.

To assist the reader, scientific terms and words that scientists use in a special way are ***italicized*** when first introduced.

Much of the discussion here about atoms, stars, galaxies, and the universe is based on my earlier book ***Everyone's Guide to Atoms, Einstein, and the Universe.***

To make this book self-contained, some material from my earlier book is summarized or replicated here. Those desiring more complete explanations of these subjects should refer to ***Everyone's Guide***.

Some have asked what motivated me to write this book. Sometime after completing ***Everyone's Guide***, I realized that many of the threads in that book wove together with a very surprising result. While the requirements of life are individually well known, little has been done to synthesize these into a comprehensive picture, and even less has been done to estimate the odds of all these requirements occurring randomly. Eventually, the intimate connection between these disparate facts became clear, and I was shocked as I computed how extraordinarily improbable these requirements are collectively. I hope you will find this remarkable tapestry of life as exciting I do.

I welcome your comments and questions. Please contact me through my website: www.**guidetothecosmos**.com.

WHAT IS SCIENCE? WHAT IS PROOF?

Before delving further into a science book, it would be well to discuss what is science and what is considered scientific proof.

Humans are model-makers. We create mental models of the world around us that enable us to understand, anticipate, and prepare for nature's challenges and opportunities. Model-making is one of humanity's most distinguishing capabilities, and science is our collective effort to model nature. Models and theories are ***effective*** if they enable ***predictions*** that are of value and if the model is ***validated***. Validation is essential but it is not the same as proof.

Scientific theories are never proven in the same sense as are mathematical theorems. In mathematics, once a theorem is proven by logical deduction, it is deemed TRUE and never needs to be proven again. For example, Euclidean geometry proves that the sum of the interior angles of any triangle equals 180 degrees. This is as true now as it was in Euclid's day 25 centuries ago. But mathematical logic cannot prove that this theorem is relevant to our universe, because Euclid's theorem is about idealized triangles. Only experiment and observation can ***validate*** or ***falsify*** the hypothesis that the real world conforms to Euclidean geometry (in fact, the real world isn't always Euclidean). Extensive testing has verified that mathematics is generally a remarkably effective model of the real world; if not, we wouldn't be able to build roads, skyscrapers, and airplanes.

However, models have limits and it's at the limits that interesting things occur. Scientists do not shrug off small discrepancies between observation and the predictions of our theories; they relish them. Even modest deviations can highlight deficiencies in current theories and lead us to better theories and a greater understanding of nature. And that, after all, is why people become scientists. The ancient

Greeks observed small deviations of the real world from Euclidean geometry and realized that the Earth is round—one of science's greatest discoveries.

Thus scientific theories are never proven, once and for all. They are validated to a certain level of precision within a certain range of conditions and are subjected to the never-ending challenge of ever more precise testing in ever broader conditions. What makes a good theory? When do scientists accept a theory as an effective model of nature? The best theories are those which: (1) make the most predictions; (2) are the most precisely validated; and (3) are validated over the broadest conditions. It also helps if the predictions are remarkable. Predicting the Sun will rise in the east impresses no one. But when Einstein's prediction that the Sun bends starlight was validated, everyone was impressed.

Prediction and the ability to falsify hypotheses are the hallmarks of science that distinguish it from other endeavors. Nobel Laureate Richard Feynman, one of the most important physicists of the 20TH century and one of my professors at Caltech, said: "The basis of science is its ability to predict."

To be a legitimate part of science, a theory or hypothesis must be testable—it must make predictions that can be confirmed or falsified. An idea that is impossible to disprove, or that does not predict anything we could possibly perceive, is not properly part of science. For example, the statement "The universe has extra dimensions that are too small to ever be detected" cannot be falsified because it asserts that something exists which cannot be found. No experiment can disprove the existence of something that is undetectable. But the statement "The universe has extra dimensions that reduce gravity by 1% per billion miles" is falsifiable. This second statement makes a prediction that can be tested, even if our present instruments lack sufficient precision. If experiments ultimately find that gravity does not decrease as claimed, that statement would be falsified.

Perhaps the premier theory of science is Einstein's Theory of Special Relativity, which has been exhaustively tested for the last 100 years with ever increasing precision. His prediction that the speed of light is the same in all directions of space is confirmed to 18 digits—one part in 1,000,000,000,000,000,000. The spacetime transform of relativity is confirmed to 22 digits, and the photon's mass is confirmed to 24 digits. To my knowledge, nothing else that any person claims to know about the physical universe has been confirmed to a precision even remotely approaching this level. Quantum Mechanics has also been exhaustively tested, and confirmed to 12 digits. Calling these pillars of science "only theories" betrays a profound lack of understanding.

Figure 1.1. Albert Einstein.

2 Atoms and Particles

The easiest approach is often to start small and build up from there. So, let's start by exploring atoms and their the role in enabling life.

Everything we see is made of atoms, and remarkably, they are the same throughout the entire universe. We observe in our most powerful telescopes exactly the same types of atoms in the most distant galaxies as we observe here on Earth. We know this because each type of atom emits its own unique type of light, its own spectrum of colors, which provides a unique fingerprint.

Albert Einstein was a physicist who became the most famous scientist in all human history. One of his achievements was proving that atoms really do exist, thus ending a debate that had roiled science for 25 centuries. Now, 100 years after Einstein devised his proof, we can actually image individual atoms using our most advanced microscopes. In figure 2.1, we see xenon atoms on a nickel plate.

Atoms are very small. How small? A billion carbon atoms lined up in a row would be about one foot long. A 130-pound person contains 6 billion, billion, billion atoms, that's 6,000,000,000,000,000,000,000,000,000 atoms. As small as atoms are, we now know they are not the smallest components of matter. Atoms can be cut into smaller pieces, and some of those pieces can be cut even further.

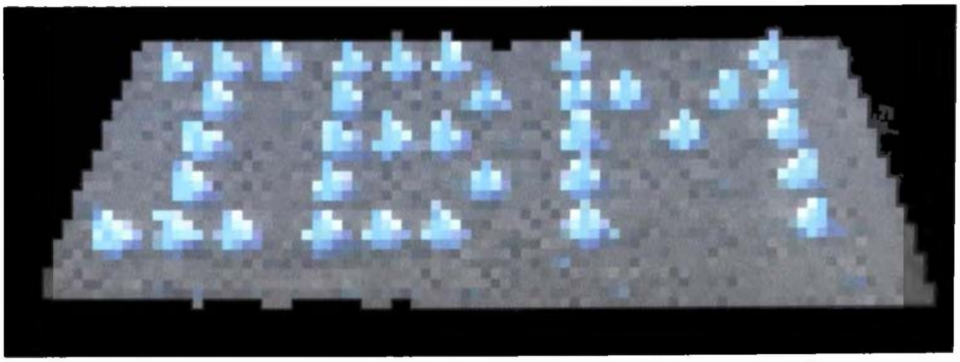

Figure 2.1. Xenon atoms on a nickel plate imaged by an atomic force microscope in the Zurich research labs of a major international corporation, whose name I forget.

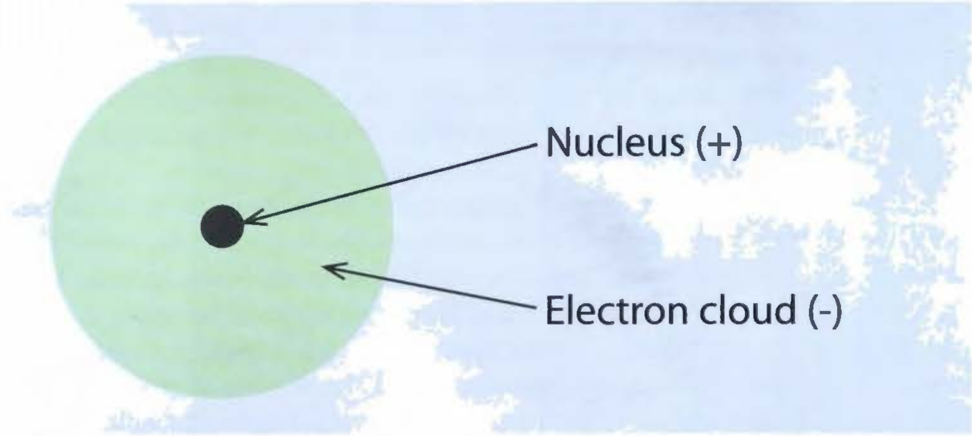

Figure 2.2. An atom has two principal parts: the central nucleus that has a positive electric charge, and the surrounding diffuse cloud of electrons that has a negative electric charge. The opposite charges hold the atom together.

If we look inside an atom, as in figure 2.2, at first we see only two parts: an inside and an outside. The inside is a ***nucleus***, which has a positive electric charge. The outside is a "cloud" of ***electrons***, which has a negative electric charge. Opposite charges (positive and negative) attract one another and hold atoms together.

This sketch in figure 2.2 is not nearly to scale. The electron cloud is really 100,000 times larger than the nucleus. If we imagine enlarging an atom until the nucleus becomes the size of a golf ball, the electron cloud would be over two miles wide. But even though it is so much smaller, the nucleus dominates the atom, containing almost all of an atom's mass—typically about 99.97%—and up to a million times more extractable energy than the surrounding electron cloud.

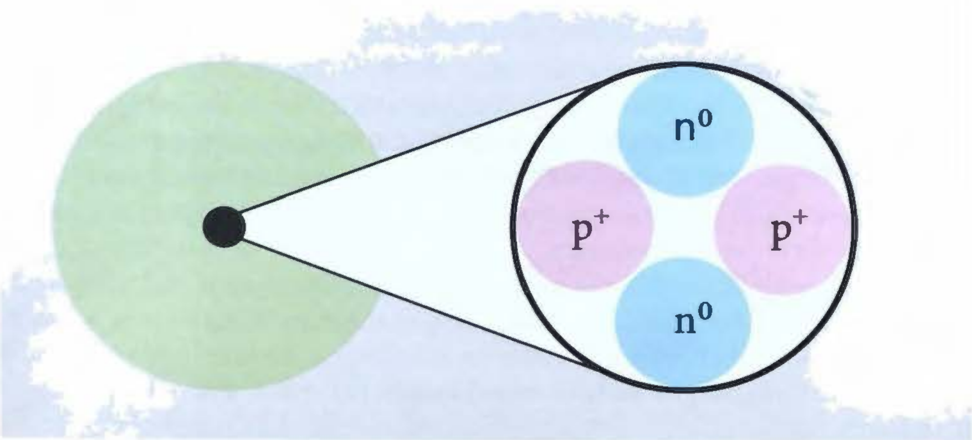

Figure 2.3. The nucleus of an atom is composed of one or more protons (p^+) that have a positive charge and zero or more neutrons (n^0) that have zero charge.

It takes energy to "cut" an atom into pieces—to pull electrons away from the nucleus—but now that's easy to do.

With even more energy we can pull nuclei apart. As shown in figure 2.3, nuclei are composed of ***protons***, which have a positive electric charge, and ***neutrons***, which have zero charge.

Each nucleus must have at least one proton so its positive charge will attract electrons. The number of protons in an atom's nucleus is its most important characteristic: its ***element number***. There are over 100 elements in the Periodic Table, each with different physical and chemical properties. Gold is element number 79 with 79 protons in its nucleus. Lead is element number 82 with 3 more protons than gold. What a difference 3 little protons make! The number of neutrons is generally similar to the number of protons, but it can vary. Two atoms with the same number of protons and different numbers of neutrons are the same element and have the same chemical properties, but are different ***isotopes***.

The most common atoms have relatively small nuclei and many of these have equal numbers of protons and neutrons. Carbon has 6 of each, nitrogen 7 of each, and oxygen 8 of each. In large nuclei, neutrons outnumber protons. In their most common isotopes, iron has 30 neutrons and 26 protons, while uranium has 146 neutrons and 92 protons.

Because atoms generally have the same number of protons and electrons, they are neutral—having zero net electric charge. Atoms with different numbers of protons and electrons have a non-zero electric charge—they are called ***ions***.

Here we have the first requirement of life—there must be atoms. Protons, neutrons, and electrons are the building blocks of atoms and are the most important three types of subatomic matter called ***particles***. If these particles did not have the right properties, life would not exist. For example, if protons were just ¼ of 1% more massive there would be no atoms in our universe and hence no life. And if protons were just ¼ of 1% less massive the process that powers the stars, and thus sustains life, would be severely compromised.

Normal hydrogen has the smallest nucleus—one proton and zero neutrons. While it's the smallest atom, hydrogen accounts for 92% of all atoms and 74% of all the atomic mass in the universe. Helium is element number 2; its normal isotope has two protons and two neutrons. Helium accounts for 7½% of all atoms and 24% of all atomic mass. Together, hydrogen and helium make up almost everything we see in the cosmos: they account for 99.8% of all atoms and 98% of all atomic mass in the universe. Of the remaining mass, 1% is oxygen, ½ of 1% is carbon, and all other elements are much more rare.

On Earth, atomic abundances are quite different. Hydrogen is much less abundant than in the universe at large. About 10% of the mass of our oceans is hydrogen, but less than 0.2% of Earth's interior is hydrogen. Helium is almost totally absent on Earth; in fact, we first discovered helium in the Sun, and only later found it on Earth.

The atomic composition of the human body is very different from that of the universe, the stars, and the Earth. By mass, we are 65% oxygen, 18% carbon, 10%

hydrogen, 3% nitrogen, 1½% calcium, and 2½% other elements.

Thus life requires not just any atoms, but atoms that are very rare. In fact, we are made of the rarest and most precious ingredients in the universe, another hint that life is special.

In addition to protons, neutrons, and electrons, many other types of particles exist, but we will only discuss two other types that are important to the story of life: ***photons*** and ***antiparticles.***

Figure 2.4. Particles and antiparticles are almost, but not exactly, opposites of one another.

Light is made of particles called photons—at the microscopic level every ray of light is composed of a stream of countless photons.

What about antiparticles? In nature, for every yin there is a yang. Just as matter is made of particles, ***antimatter*** is made of antiparticles. For each type of particle, there is a corresponding type of antiparticle. An antiparticle has the same mass as its particle partner, but all of its other characteristics, such as its electric charge, are exactly the opposite. If a particle and its antiparticle combine, they annihilate—they totally destroy one another leaving behind only energy—no residual charge, no residual matter, no residual anything. After the pair annihilates, no trace remains that the particle or the antiparticle ever existed.

When the universe began, it had just as many antiparticles as particles. Before the universe was one second old, almost every antiparticle annihilated and took a particle with it. Why then, is there anything at all in the universe today? Only because nature is not exactly symmetric, as figure 2.4 shows. My Ph.D. thesis experiment and others showed that a single aspect of nature is just slightly fonder of particles than it is of antiparticles. This otherwise obscure natural phenomenon led to a slight excess of particles during the universe's first second. Before the great annihilation, for every one billion antiparticles there were one billion ***and one*** particles. When the billion antiparticles annihilated, they took a billion particles with them into oblivion and left behind one sole survivor. Everything we see in the universe today is made of those very rare survivors—the one in a billion.

How lucky is that?

3
Stars Make Life Possible

Stars are the building blocks of the universe. They provide the heat, light, and materials necessary for life. Without stars, the universe would be bitterly cold, dark, desolate, and lifeless. Stars make the universe beautiful and habitable.

Shortly after the Big Bang, when the universe came into existence, hydrogen and helium accounted for all but one atom in a million. There was just a dash of lithium, but not a single atom of carbon or oxygen in the entire universe. Stars created the atoms that life requires.

In regions far from the warmth of stars, the temperature of our universe has dropped to $-455\ ^{o}F$. At this temperature atoms have 100 times less heat than ice. Stars provide the warmth necessary for life.

As dismal as the average temperature of the universe is, its density is even less encouraging. The average distance between atoms is 17 feet. At that density, to make a single human being, one would need to gather all the atoms within a giant ball as big as the orbit of Mars around the Sun. Stars bring atoms together in sufficient numbers for life to exist.

Stars are balls of gas so massive that their self-gravity sustains nature's ultimate fire: ***nuclear fusion***. Fusion creates the light that sustains life and makes stars twinkle in the sky. Fusion in stars also creates the atoms from which planets and all living creatures are made.

The life and death of stars is determined by the interplay of gravity and pressure. Gravity, driven by a star's mass, strives to crush it, while pressure, created in a star's core, tries to blow it apart. The pressure derives from the properties of subatomic particles. Since each star is made of the same types of particles, the only variable factor is the star's mass.

Stars are born when immense clouds of gas collapse. Since all types of matter attract one another by gravity, one might think a gas cloud would immediately collapse because all of its particles would fall directly into its center. Actually, collapse is surprisingly rare. Even now, 14 billion years after the Big Bang, only 10% of the atoms in the universe are in stars. One reason that more matter has not collapsed is that the rapid expansion of the universe spreads matter throughout an ever-increasing volume. Another reason is that gas clouds are typically vast and of nearly

Figure 3.1. Stars are born from the collapse of immense gas clouds. One such cloud is the Eagle Nebula, seen in green in the upper left corner with talons in front and wings that span 200 trillion miles. Image by NASA Spitzer.

uniform density. These clouds can remain relatively unchanged for hundreds of millions of years or more.

Nebulae are gas clouds illuminated by stars, and are some of the most beautiful sights in the heavens. Figure 3.1 shows an image of the Eagle Nebula (in green, in the upper left corner). The wing span of this eagle is 200 trillion miles, about a million times the diameter of Earth's orbit around the Sun. Our entire solar system is smaller than the smallest dot in this image.

Gas clouds are quite stable, but nothing in the universe lasts forever. Galaxies often cluster in large groups and sometimes pass very close to one another, or even collide. Since galaxies contain hundreds of billions of stars, the immense gravitational shock of a galactic close encounter often disrupts gas clouds in both galaxies. Supernovae, the explosions of massive stars, also create shock waves that disrupt gas clouds. Whatever the cause, once part of a cloud becomes substantially denser than average, its tranquil balance ends. Denser regions have stronger gravity and pull in surrounding matter, leading to the formation of a cluster of new stars.

The Pillars of Creation, shown in figure 3.2, tower 6 trillion miles. Here new stars, seen as pink spots, are forming in collapsing gas clouds. As gas falls into a collapsing region, it heats up and creates pressure that could eventually stop further collapse. This heat energy must be dissipated if the cloud is to continue collapsing. New stars form only if the gas can radiate away enough energy, and if

Figure 3.2. The Pillars of Creation, the talons of the Eagle Nebula, tower up to 6 trillion miles high. The pink spots are new stars forming as the gas clouds collapse. Image by NASA Hubble.

the gravitational imbalance is sufficient. The presence of heavier elements, such as carbon and oxygen, greatly assists in radiating heat and facilitating star formation. These heavier elements come from the explosive deaths of previous generations of stars.

As gas clouds collapse, they spin faster and faster, just as figure skaters do when they pull in their arms and legs. Collisions among the collapsing gas particles flatten the gas into a disk. Particles in oblique orbits cross the disk twice per orbit and collide with particles in the disk. These collisions gradually equalize particle velocities. Eventually, most particles fall into the disk. It's easier to go with the flow than to swim upstream. As the disk grows denser, its own self-gravity flattens it further.

The entire collapse process can take hundreds of thousands of years. Eventually, most of the gas collapses into a small central ball called a ***proto-star***; it is small only compared to the original gas cloud. Collapse can be relentless and efficient.

Figure 3.3. This NASA illustration compares the sizes and colors of various star types. Our Sun is now a yellow dwarf but will become a red giant near the end its life in about five billion years.

Nearly 99.9% of the mass of our solar system collapsed into the Sun; the remaining gas formed planets, moons, asteroids, comets, and assorted debris.

Proto-stars with masses less than 8% of the mass of our Sun (which we shall abbreviate ***Msun***) don't have enough gravity to sustain fusion and they never become true stars; these are called ***brown dwarfs***. In a proto-star with a mass greater than 8% of ***Msun***, gravity squeezes its gas until its central temperature is high enough to initiate nuclear fusion. Stars just barely massive enough to sustain nuclear fusion are very dim and are called ***red dwarfs***. Our Sun is more massive than an average star; it is a ***yellow dwarf*** and its core temperature is now 30 million ^{O}F. Today, the heaviest stars have masses of up to 150 ***Msun*** and are called ***blue-white supergiants***. Figure 3.3 shows a comparison of star sizes, masses, and colors. As with most celestial entities, there are far more small stars than large stars. As you can see in this illustration, blue-white supergiants are much smaller than ***red giants***. This is because the names "dwarf" and "giant" are not assigned based on size. Only a few stars are so close that astronomers can directly measure their actual size. Rather, astronomers call dim stars "dwarfs" and bright stars "giants", without regard to what their physical sizes might actually be.

When nuclear fusion starts in its core, a proto-star becomes a true star. In addition to enormous light output, stars also produce powerful ***stellar winds***, streams

of high-energy particles. Powerful stellar winds from new stars blow away any surrounding gas that has not already condensed into a large body, such as a planet.

Our Sun emits one million tons of particles each second in its solar wind. This is in addition to the 4 million tons of mass it converts into heat and light every second. Thus our Sun is on a weight-loss program, losing 5 million tons per second.

Stellar winds from new stars effectively prevent an entire gas cloud from collapsing into just a few stars. They prevent stars from becoming extraordinarily heavy and, therefore, short-lived and unsuitable for life. Nature produces a large number of moderately sized, long-lived stars around which life can develop and saves the remaining gas for later generations of stars.

Some say diamonds are forever; what about stars? Stars are mortal and they too pass with time. But it can be a very long time indeed, from millions of years to millions of millions of years.

But why are stars long-lived at all? Why doesn't collapsing gas continue to collapse down to "nothing"? If you drop a rock in the ocean, it doesn't stop until it hits bottom. Why does the gas stop falling? It stops because of nuclear fusion in the star's core. Without fusion, our Sun would have burned out in a few thousand years and none of us would be here.

Nuclear fusion is nature's ultimate fire. It depends on the properties of atomic nuclei and can produce millions of times more energy than a conventional fire. Fusion changes everything. When a star's core temperature rises to tens of millions of degrees, hydrogen in the core begins to fuse. This releases a tremendous amount of heat, leading to a correspondingly tremendous pressure that stops the star's further collapse.

Nuclear fusion gives stars a long and stable life, a long-lasting equilibrium, and a balance between gravity and pressure, as illustrated in figure 3.4. This delicate balance can keep a star burning at a nearly constant rate for billions of years. Our Sun is a huge inferno, a million times Earth's size, with an extremely precise thermostat on which our lives depend. If the Sun's energy output—its ***luminosity***—doubled, Earth would receive as much solar energy as Venus does now, with its average temperature of 800 ^{O}F. If the Sun's luminosity were halved, Earth might have the climate that Mars does now, with an average temperature of −80 ^{O}F.

Life requires much more favorable temperatures. The ***habitable zone*** of our solar system is generally considered to be the region where water can be liquid. While it is not absolutely impossible for some form of life to exist elsewhere, the sweet spot is right here. The habitable zone is a narrow band centered on Earth's orbit, as illustrated in figure 5.2. For Earth to remain habitable, the Sun's luminosity cannot vary by more than ±10%, and perhaps much less. Multi-cellular life evolved on Earth in the last 600 million years, during which the Sun's luminosity varied only ±3%. Compare that variation to the full range of stellar luminosities: the brightest star is a billion times brighter than the dimmest star. Our Sun is near the middle of this range, with a thermostat that holds its luminosity stable to better than 1 part in a million of this range. If your home heating system were that precise, the temperature in your house would never vary by more than 1/10,000TH

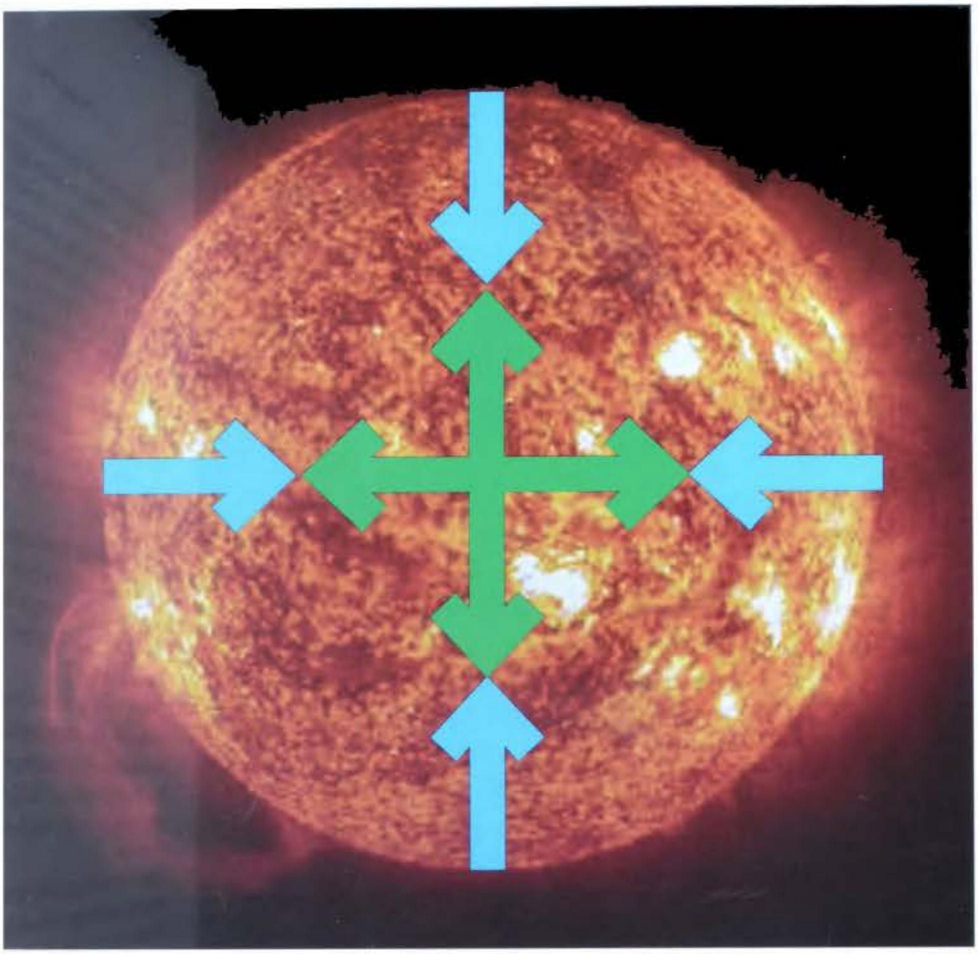

Figure 3.4. A star can exist for billions of years in a delicate balance of gravity and pressure. Gravity acts to crush it (blue arrows) while pressure acts to blow it apart (green arrows). Image of our Sun by NASA SOHO.

of a degree. We are in a ***Goldilocks Zone***, where the temperature is stable, not too hot and not too cold, but just right.

Clearly, we've got it good. But how long will the good times last?

While hydrogen fusion continues to burn in their cores, stars are remarkably stable. Our Sun's hydrogen fusion stage will last 10 billion years; we're now at half-time. During its 10 billion year life, a star with our Sun's mass converts 10% of its original hydrogen into helium. Being heavier, helium sinks to the center and pushes out the hydrogen. Eventually, helium starves the core of hydrogen fuel and ends the hydrogen fusion stage. More massive stars burn their hydrogen much more rapidly and die much sooner; less massive stars are very dim and live much longer. Stars 25 times more massive than our Sun burn hydrogen 36,000 times faster and run out of hydrogen in only 7 million years. Even though they start with so much more fuel, their lives are 1500 times shorter.

Regardless of its mass, every star ultimately runs out of hydrogen in its core. Its pressure wanes and gravity finally wins the epic battle with pressure. Gravity compresses the core and pushes its temperature ever higher. For stars with masses of at least ½ ***Msun***, core temperatures eventually reach 300 million ^{O}F and the next stage begins: helium fusion. Three helium nuclei fuse to produce carbon. As the core reaches this enormous temperature, the resulting pressure pushes the star's outer layers farther out, dramatically expanding the star, and turning it into a red giant. Look again at figure 3.3. When our Sun becomes a red giant, it will engulf Mercury and Venus, and may extend almost to Earth's orbit. We need to be out of here well before then.

When the supply of helium in the star's core is depleted, it may contract further and become even hotter. At higher core temperatures, additional fusion stages produce nitrogen, oxygen, and other elements. More massive stars reach higher core temperatures, progress through more fusion stages, and produce ever heavier elements. The most massive stars reach core temperatures of 7 billion ^{O}F, hot enough to produce iron. Each stage of nuclear fusion has a drastically shorter duration than the prior stage. The fusion stage that produces iron lasts only one Earth-day—less than one billionth as long as the hydrogen fusion stage. Hence, a star's life is only slightly longer than the duration of its hydrogen fusion stage.

Eventually, when all its nuclear fuels are consumed, a star's life ends. As fusion's heat and pressure wane, gravity relentlessly compresses the core. As the core contracts, gravity becomes even stronger because this force increases rapidly as distances shrink. Eventually, the core implodes catastrophically, releasing almost as much energy in one brilliant flash as the star may have produced in its entire life. The energy released by the implosion of the core blasts the star's outer layers out into space, along with the new atoms it created.

The explosion at the end of a star's life can create a beautiful nebula, such as the Cat's Eye Nebula shown in figure 3.5. Here, the collapsed core became a ***white dwarf***, the white dot in the center. The star's outer layers were blown off into space by the explosion and formed the surrounding nebula. This will be the fate of our Sun in about five billion years.

The most massive stars die in the most spectacular explosions called ***supernovae***. SN1987a is one of the most famous of all supernovae. (Supernovae are named "SN" followed by the year of their occurrence, followed by one or more letters; "a" is the first supernova of each year.) SN1987a occurred in the Large Magellanic Cloud, a satellite galaxy of our own Milky Way, one million, million, million miles from Earth. For such vast distances it is more convenient to measure distances in ***light-years*** rather than miles, with a light-year being the distance light travels in one year—about 6 trillion miles. As we will discuss below, SN1987a is 168,000 light-years away. But as far as that is, it was the nearest supernova since the invention of the telescope, so astronomers went wild. The first person to see SN1987a was an astronomer walking to work who happened to look up at the night sky. The supernova was bright enough to catch his eye even from that great distance and even without a telescope or binoculars.

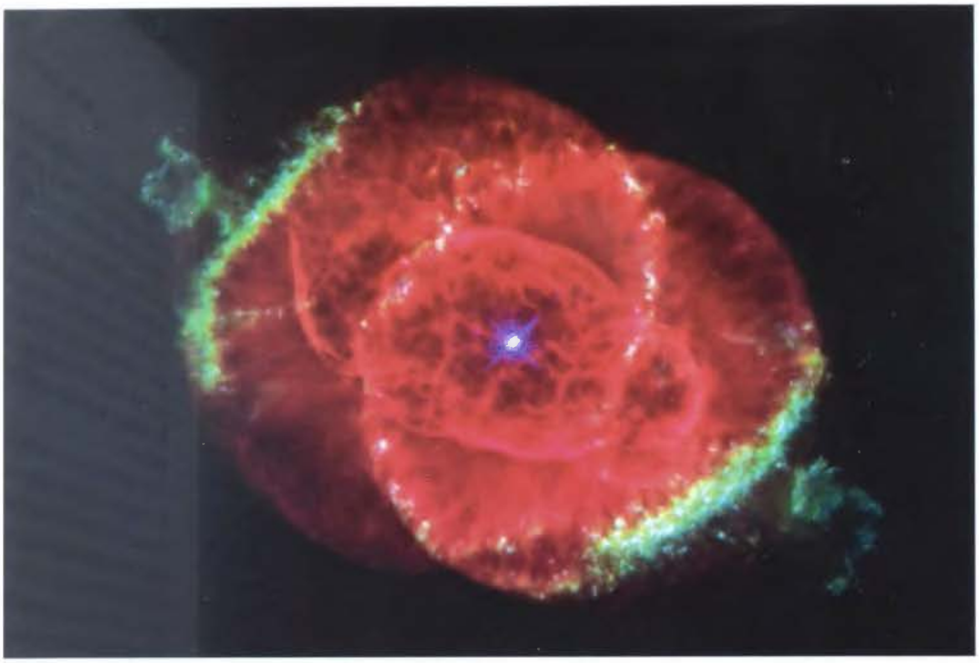

Figure 3.5. The Cat's Eye Nebula is the aftermath of the explosion of a Sun-like star that reached the end of its life. The white dot in the center is the collapsed core and the surrounding nebula was formed by the star's outer layers that were blown away. The Cat's Eye is 3000 light-years away. Image by NASA Hubble.

For several weeks, supernovae can be brighter than an entire galaxy. The amount of energy they release is truly incomprehensible—up to 10 million times more energy than the detonation of a stack of dynamite as large as our Sun.

SN1987a provided an excellent cosmic yardstick. A ring of previously ejected gas, shown in figure 3.6, brightened dramatically 245 days after the initial explosion when it was hit by the supernova's immense blast of light. Since the speed of light is well-known and always the same, the diameter of that ring must be 8 trillion miles (490 light-days). By measuring the angle X subtended by the ring, geometry tells us, with a precision of 2%, that this object is 168,000 light-years away and that the explosion we observed in 1987 occurred at that remote site 168,000 years earlier. SN1987a provides simple and compelling proof that the universe must be at least 168,000 years old. In later chapters, we will find that our universe is actually 13.7 billion years old.

The cosmos is an efficient recycler. The spectacular death of a star sets the stage for new beginnings. Shock waves from stellar explosions often initiate the collapse of neighboring gas clouds and the formation of new stars. Vital elements created in stars are dispersed into the galaxy by stars' violent deaths. The collapsed cores that remain are the most exotic objects in the universe: white dwarfs, ***neutron stars***, and ***black holes***. Examples of these are found in figure 3.5 (white dwarf), figure 3.7 (neutron star), and figure 3.8 (black hole).

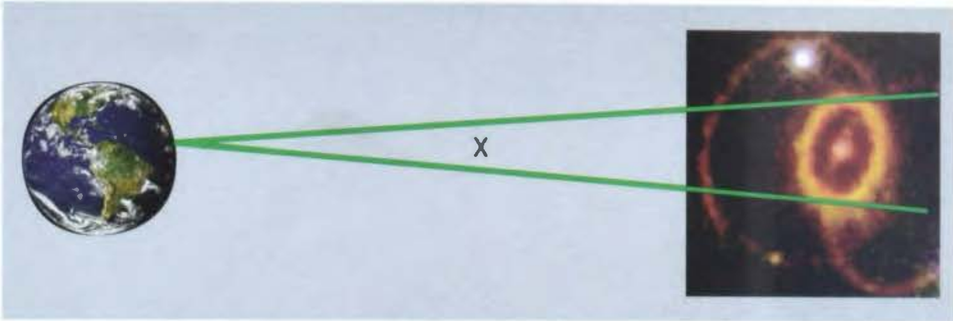

Figure 3.6. Astronomers observed that the inner ring of SN1987a, imaged by NASA/Hubble, brightened 245 days after the supernova. This means the ring's diameter is 8 trillion miles. By measuring angle X, the distance to the supernova is found to be 168,000 light-years, measured with a precision of 2%.

Before their demise, massive stars create all the elements with masses up through iron by nuclear fusion. Because iron has the most tightly bound atomic nucleus, no energy can be released by fusing it into heavier elements. Once a star has finished producing iron, it can no longer generate the energy and pressure needed to prevent gravitational collapse, and it dies. Heavier elements, including silver, gold, lead, and uranium, are produced during the instant of the star's explosive death. When a stellar core implodes, it collapses to something dramatically smaller, releasing an immense amount of gravitational potential energy and increasing the star's luminosity up to 100-billion-fold. Some of that energy is absorbed in converting iron into heavier elements. Since these elements are less tightly bound than iron, fusing iron to create them absorbs energy from the blast.

Atoms heavier than helium, which are required for any form of life, are made only in stars and are dispersed by their explosive deaths. Interstellar gases enriched with these atoms later collapse to form new stars and new planets. This cycle is repeated over and over. Each generation of stars increases the amount of carbon and oxygen in the galaxy. Judging from the concentration of various elements in our solar system, the Sun may be a third-generation star; the material of our solar system may have come from the death of an earlier star that was itself made of material from the death of an even earlier star.

All the atoms in Earth and in our bodies, other than hydrogen, were made in the centers of massive, extremely hot stars that exploded at least 5 billion years ago. Hydrogen nuclei, the other 10% of our body weight, were produced in the first millionth of a second after the Big Bang; these are almost 14 billion years old. But don't feel like Methuselah. Regardless of their age, atoms are always in pristine, brand-new condition. Atoms are too small to have a clock—they never age, they never wear out, and they never run down.

Atoms are timeless.

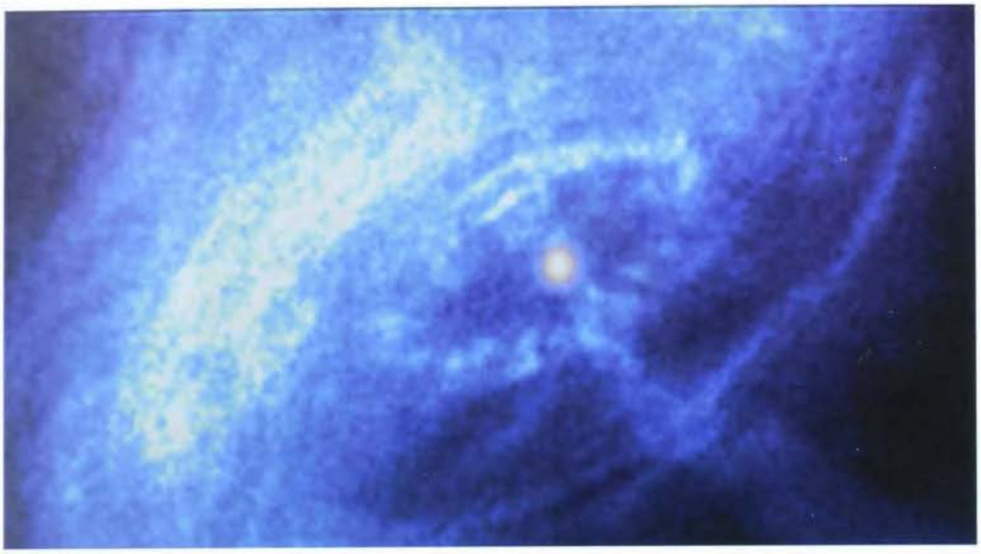

Figure 3.7. NASA Chandra x-ray image of the neutron star (central white dot) at the heart of the Crab Nebula, 6500 light-years away. This neutron star, more massive than our Sun and yet compressed into a ball less than ten miles across, rotates 33 times per second, sweeping a beam of particles across the cosmos like a lighthouse beacon.

Figure 3.8. Radio telescope image of an accretion disk and jets from a black hole in Cygnus A, 600 million light-years away. Matter falling toward the black hole forms a swirling accretion disk, the central white dot, around the black hole. We cannot see the black hole itself because it emits no light (it's black). The two jets shooting out along the rotating black hole's poles span 500,000 light-years—five times the size of our galaxy. This black hole has an estimated mass of one billion times the mass of our Sun, all of which is compressed into a ball trillions of times smaller than a single atom. Astronomers believe that all major galaxies harbor super-massive black holes at their centers. Image by VLA, NRAO, AUI.

4
Galaxies and the Universe

We all know our universe is immense. But just how immense is it? First, let's consider how much it contains. We'll start with something close to home: figure 4.1 shows an image of our Sun. The small white dot in the upper right was added to show how small Earth would be if it were in this image—can you see it? Our entire world is barely perceptible next to a fairly average star. The spectacular prominence flaring out from the Sun is 40 times larger than Earth. Fortunately, Earth is never this close to the Sun. If it were, we would all need SPF 999,999 sunscreen.

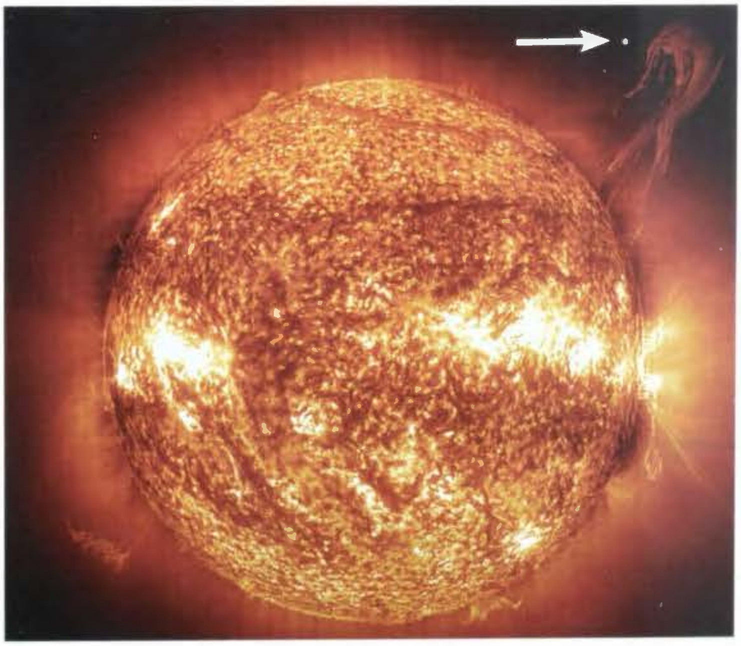

Figure 4.1. Above image by NASA SOHO shows our Sun on a "bad hair" day. The white dot indicated by the arrow was added to show how large Earth would be on the same scale. Fortunately we are never this close to the Sun.

Figure 4.2. The Andromeda Galaxy is the largest and most distant object that can be observed with the naked eye. Somewhat larger than our own galaxy, Andromeda is our largest neighboring galaxy, containing a trillion stars. Image by John Lanoue.

Our Sun is the nearest star, and it sustains our lives. But it is only one of so many, many stars.

Looking out into the cosmos, we see beautiful ***galaxies***—giant assemblies of stars like our Sun. Figure 4.2 shows an image of Andromeda, our largest neighboring galaxy. Andromeda is a classic spiral galaxy, somewhat larger and more massive than our own Milky Way. It is also the largest and most distant object visible to the naked eye. Andromeda is estimated to contain one trillion stars, and is 2½ million light-years away. Thus light emitted by this galaxy takes 2½ million years to reach us. Andromeda is moving toward us at over 250,000 mph and will collide with our galaxy, the Milky Way, in about 3 billion years, merging over the following few billion years to form a single, very massive galaxy. While stars are generally very far apart compared to their size, the distance between galaxies is often only a few times their diameters. Thus galactic collisions and mergers are common. That's how the big galaxies get big. The Milky Way may have absorbed several dozen small galaxies to reach its current status—the second-largest behemoth in the ***Local Group***, a ***cluster*** of about 30 galaxies. As with stars, there are far more small galaxies than large ones.

When galaxies collide, they can pass completely through one another without any of their stars colliding. This is because there is so much empty space between stars. The nearest star to our Sun is over 4 light-years away—30 million solar diameters. If people were spaced in the same proportion, there

would only be one human on Earth. If a star from Andromeda were to pass through our neighborhood, the probability of the Sun being hit is about the same as the probability of you being hit by the next meteor to land on Earth. Of course, there would not be just one Andromeda star passing through; there could be billions of them. Still, the odds of the Sun being hit are very low.

While star-on-star collisions are unlikely, the gravitational shock of immense, fast-moving galaxies will wreak havoc on the peaceful, stable orbits of stars in both galaxies. Vast numbers of stars will be thrown out into the great beyond, while other stars will be flung into super-massive black holes. There will be enormous ***starbursts***, vast numbers of new stars created by the gravitational shock of the galactic collision, as well as a tremendous increase in extremely violent events such as supernovae and radiation from accretion disks. An example of this is shown in figure 4.3. Notice the large blue areas in the colliding Mice Galaxies. Blue light comes from very massive, young stars that shine brilliantly, are short-lived, and die violently. Figure 4.4 shows the stunning aftermath of another galactic close encounter. Galaxies M81 and M82 are 150,000 light-years apart and 12 million light years from us. They are locked in a gravitational embrace that periodically brings them close together, setting off spectacular fireworks as seen in M82, the Cigar Galaxy. In addition to starbursts, the Cigar Galaxy displays light from polycyclic aromatic hydrocarbons (PAHs). PAHs are possible building blocks for the most basic forms of life, although they are considered carcinogenic for humans. This is an example of the cosmos producing large quantities of organic compounds. Amino acids have been found in asteroids, comets, and interstellar gas.

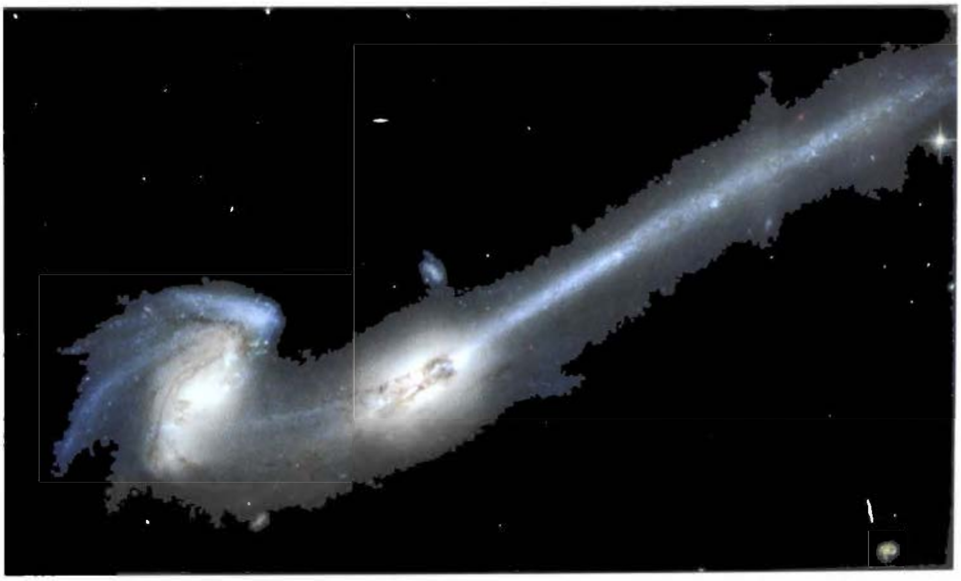

Figure 4.3. The Mice Galaxies are 300 million light-years away. We see the aftermath of their great collision that cast countless stars out into long "tails" and initiated immense starbursts that emit blue light. Image by NASA Hubble.

Figure 4.4. Above: Galaxies M81 (left) and M82 (right) are gravitationally bound to one another, and periodically come too close for comfort. Below: A close-up of M82 shows the cataclysmic result of their last close encounter. Images by NASA/Hubble.

Figure 4.5. A NASA / Caltech reconstruction of our galaxy, the Milky Way, showing its barred spiral structure. Our galaxy is 100,000 light-years across, and we are perfectly situated (tip of yellow arrow) in its Goldilocks Zone, 27,000 light-years from the center.

When Andromeda eventually arrives, which side of our galaxy becomes ground zero will make a great deal of difference to our solar system (and to us, if we're still here). We cannot yet predict where the impact will occur—but let's hope we're in the cheap seats, far from the action.

But all that is 3 billion years from now. Let's get back to today.

Earlier, I mentioned that Andromeda is 2½ million light-years away and thus it takes light 2½ million years to reach us. This means that the light reaching our telescopes today began its journey 2½ million years ago. Hence the image we see today is really not what Andromeda looks like today—it's what that great galaxy looked like 2½ million years ago.

Thus we can think of telescopes as being a type of time machine. Telescopes don't take our bodies back to the good old days (whenever that was) but they do take our eyes back and allow us to see the past as it ***is*** actually happening. Astronomers have a great advantage—they don't have to guess what the universe was like in the past; they can actually see it as it ***is*** in the past because its image is preserved in the time capsule of light traveling through the vastness of space.

I would love to show you an image of our Milky Way comparable to that of Andromeda, but we would have to move our telescopes a trillion, trillion miles out into space to get the same panoramic view. Instead, figure 4.5 shows a remarkable NASA/Caltech reconstruction of what we think our galaxy looks like from

Figure 4.6. The Sombrero Galaxy is 28 million light-years away with a mass of 800 billion suns. Image by NASA Hubble.

the outside based on what we observe from the inside. The Milky Way is a barred spiral galaxy containing about 300 billion stars, with a central bar connected to two major spiral arms, each with several spurs. It is 100,000 light-years across and Earth is perfectly situated 27,000 light-years from its center.

Figure 4.6 is an image of the Sombrero Galaxy, which is even more massive than Andromeda. It has a black hole at its center with a mass of 1 billion ***Msun***. The Sombrero is 28 million light-years away. Its light that we see today began its journey 28 million years ago—millions of years before human beings existed.

Looking out farther, we find that galaxies are often in clusters, some containing thousands of galaxies. Figure 4.7 is an image of the Hercules Galaxy Cluster 400 million light-years away. On the left, we see the aftermath of a close encounter between two galaxies. A long filament of stars has been torn loose, as if it were cotton candy, and is now stretched between the galaxies. The light we see today began its journey before dinosaurs walked the Earth.

Figure 4.8 shows the spectacular Hubble Ultra Deep Field (HUDF) image in which we can see almost to the very edge of our universe and almost to the very beginning of time. Light from some of the galaxies seen here has taken 13 billion years to reach us. That journey began billions of years before the Sun and the Earth even existed. The area covered by the HUDF image is less than a tenth of a millionth of the entire sky. But in this very small area, there are over 10,000 galaxies that had never been seen before.

The HUDF image is literally a shot in the dark. In 2003, the Hubble team decided to take a gamble, hoping to see farther than anyone ever had before. They chose to invest precious telescope time and risk coming up empty-handed. Imagine, for a moment, that galaxies are trees, and we are in a tree in the middle of a

Figure 4.7. The Hercules Galaxy Cluster is 400 million light-years away. On the left, a stream of stars has been torn from two galaxies that collided. Image by J.C. Cullandre, CFHT.

great forest. It's hard to see distant trees because so many closer ones block our view. To see very distant trees, we have to find a gap between the nearby ones.

Most "Kodak moments" are captured in a $1/60^{TH}$ of a second or less. The Hubble team aimed the world's finest telescope at a seemingly empty spot in the sky and opened the shutter for a total of one million seconds (a 12-day exposure taken in small increments over a one month period). Aiming at empty space let them avoid the glare of nearer and brighter objects, but they didn't know what, if anything, they would see. After using all that valuable telescope time, they could have ended up with a blank image; that part of space could have been as empty as it first appeared. But it was not.

The gamble paid off. Hubble saw farther than ever before, and captured an image that casts new light on our understanding of the universe. What a magnificent achievement!

With the HUDF image and others, we are confident that our universe contains over 100 billion galaxies, each with an average of 100 billion stars. Astronomers fondly say: there are more stars in the heavens than grains of sand on all the beaches of all the oceans on Earth.

I estimate there are at least 1000 times more stars in our universe (10^{22}) than grains of sand on all the world's beaches (10^{19}). That is how immense our universe is in terms of what it contains. (Let me digress to explain the notation just used. It is sometimes easier to write very large numbers in scientific notation: 10^{22} is a 1 followed by 22 zeros, which equals 10,000 billion, billion. Very small numbers can be written 10^{-22}, which as a decimal fraction has 21 zeros and a 1 in the 22^{ND} digit. 10^{-22} equals $1/10^{22}$.)

Figure 4.8. NASA's Hubble Ultra-Deep Field image ("HUDF") contains over 10,000 galaxies and takes us to the edge of our universe and back almost to the beginning of time. Here we see some galaxies as they were 13 billion years ago.

Next let's discuss what we mean by "our" universe and how large it is. Physicists are practical people and we have a practical definition of "our" universe. We define it to be everything that we can possibly see by any conceivable means and everything that could possibly influence us in any conceivable way. Einstein declared that no object and no influence could move through space faster than the speed of light through empty space. Over the last 100 years, Einstein's claim has been extensively and precisely confirmed by innumerable experiments. For example, I worked with particles that were accelerated to extremely high energies—their speeds reached 99.999,999,97% of the speed of light, but no faster. We also know, as is discussed below, that the universe is 13.7 billion years old. These two facts mean that since the beginning of time, nothing could have traveled more than 13.7 billion light-years. As yet, we cannot observe nor be influenced by anything that is farther away, thus such things are not in our universe. Hence, as figure 4.9 shows, our universe is a sphere centered on Earth; the sphere's radius is the maximum distance light could have traveled since the beginning of time. The galaxy on the far right may very well exist but it is not in our universe because it is too far away for us to observe or be influenced by, as yet.

Another key fact to know about our universe is that it is filled with low-energy radiation called the *CMB* ("Cosmic Microwave Background"). The CMB is a relic of the Big Bang—it is the afterglow of the primordial fireball that was our universe

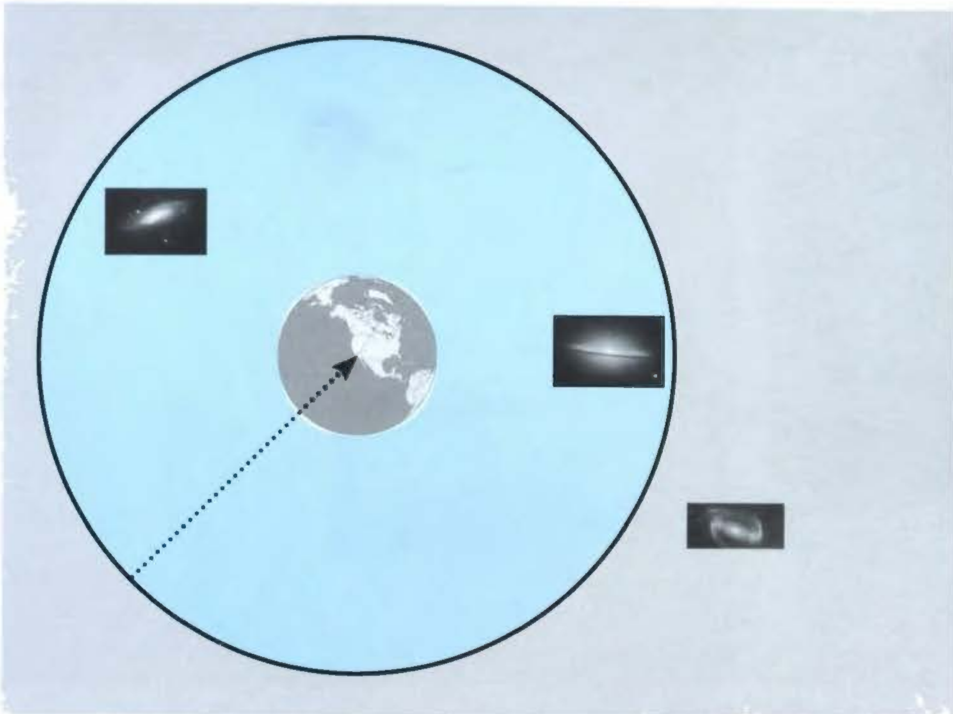

Figure 4.9. "Our universe" (blue) is defined as everything we can possibly see or possibly be influenced by in any conceivable way. Since nothing can travel through empty space faster than light, our universe is a sphere centered on Earth, whose radius (dotted arrow) is the maximum distance light can have traveled since the beginning of time 13.7 billion years ago. The galaxy on the lower right is too far away for its light to have reached us by now—it is therefore not in our universe.

in the beginning. As the universe expanded, it cooled and the energy of the CMB steadily declined. Yet it remains throughout the universe and vastly outnumbers all other particles. NASA's WMAP satellite recently took the spectacular image of the CMB seen in figure 4.10. This shows what the universe looked like when it was 380,000 years old, only 1/36,000TH of its current age. This is a baby picture of our universe. If we compare the universe to a 100-year-old person, this is a picture of the fetus one day after conception. We can already see some "arms and legs"—the red areas, where the universe was very slightly more dense, grew to become clusters of galaxies, while the blue areas, where it was very slightly less dense, grew to become great voids. These differences are very slight indeed, only about one part in 100,000. The exquisite uniformity of the CMB across the entire sky is compelling confirmation of the core message of the Big Bang theory—that everything in the universe was in one place at one moment in time.

This is confirmed by precise observations that show the universe is expanding. First discovered by Edwin Hubble, after whom the space telescope is named, astronomers observe that all distant galaxies are moving away from us in a very

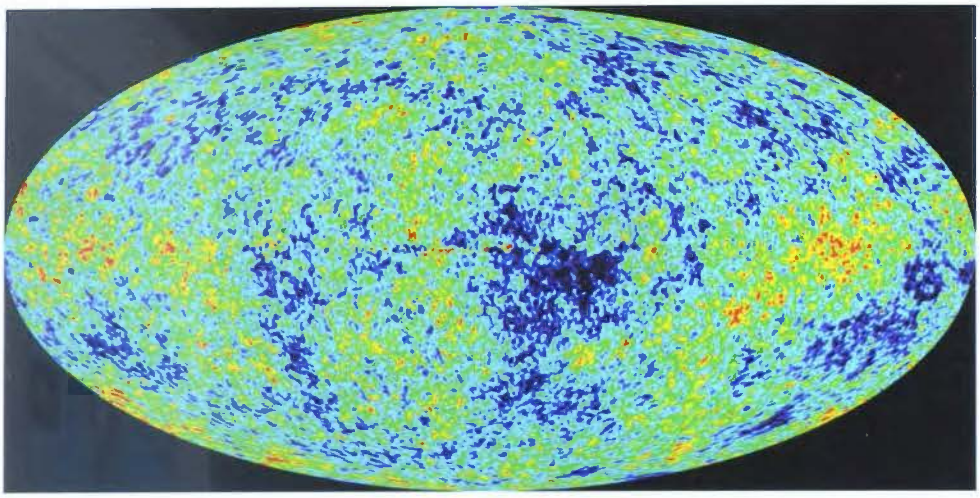

Figure 4.10. The NASA WMAP image of the Cosmic Microwave Background (CMB) radiation shows the universe at 1/36,000TH of its current age of 13.7 billion years. The CMB is extremely uniform—the red areas were only 1/100,000TH more dense than the blue areas. The red areas have become galaxy clusters.

definite manner—their velocities are proportional to their distances from us. Thus a galaxy that is twice as far away as another galaxy is seen to be moving away at twice the velocity of that other galaxy, and a galaxy that is ten times farther is moving ten times faster. Actually, we don't know whether the galaxies are moving away from us or we are moving away from them, or some combination. It turns out that it doesn't matter—the key fact is that all galaxies are moving apart.

Imagine for a moment that a motion picture had been taken of all the galaxies over billions of years. Now imagine playing the movie backwards, starting from today and proceeding back in time. Viewed backwards in time, it would appear that galaxies twice as far away would be moving ***toward*** us twice as fast and those ten times farther away would be moving toward us ten times faster. This means every galaxy would reach us at the same time, since the farther galaxies are moving faster in exactly the right proportion. Thus all galaxies must have been in one place at one moment in the distant past—a moment we call the Big Bang.

From the observed expansion rate of the universe and the knowledge that everything was once in a single place, we can compute the amount of time that the universe has been expanding—and that is the age of the universe. The result is 13.7 billion years, which is measured with a precision of 1% (meaning it is between 13.5 and 13.9 billion years old).

5
Earth Is Special

The cosmos contains vast numbers of stars and presumably vast numbers of planets orbiting those stars. But our home is not just another rock in an immense universe. Earth really is a very special place. Let's discuss some of the remarkable characteristics that make Earth special, starting with the wide-angle view and gradually zooming in.

IN THE GOLDILOCKS ZONE OF THE RIGHT GALAXY

Firstly, the Milky Way is a good galaxy to call home. Some galaxies emit indescribably enormous amounts of radiation from their centers due to voracious supermassive black holes. The radiation from some galaxy cores would not just sterilize a planet, it could destroy entire solar systems. Our galaxy is far more sedate and less dangerous. Certainly, it is now. And, perhaps, it has always been relatively tranquil. Sagittarius A*, the central black hole in our galaxy, has a mass of "only" 4 million ***Msun***, 3000 times less than the most massive black holes. This indicates that Sag A* (as its friends call it) has consumed much less matter and emitted much less radiation than many of its heavier cousins.

Our galaxy resides in a relatively placid group of about 40 galaxies. Within the Local Group, the Milky Way and Andromeda are the only major galaxies (see figures 4.5 and 4.2) and all the others are much smaller. Thus it's likely that the Milky Way has never suffered a collision with another major galaxy, at least so far.

Our solar system is favorably positioned within our galaxy. We are far enough from the galactic center, 27,000 light-years, to avoid its hazards. As sedate as the Milky Way is compared with some galaxies, all galactic centers are dangerous places. The most massive black holes are in the centers of galaxies, as is the most intense radiation. Also, the density of stars at the center of our galaxy is 100 million times larger than in our neighborhood. Stars near the center of our galaxy are moving at up to 3 million mph. The combination of so many stars moving so rapidly makes galactic cores shooting galleries. It is much safer to be far from the core—but not too far. The outer reaches of galaxies have very little carbon, oxygen,

Figure 5.1. "The Blue Marble" is a composite image of Earth, constructed from numerous smaller images taken by NASA satellites.

and other elements life requires. These elements are made in very massive stars and there are far fewer of those out in the boondocks. Our solar system is in a very favorable neighborhood in the suburbs, not too close and not too far. Astrophysicists call this the galaxy's "Goldilocks Zone."

Our solar system is also special in several other ways.

AT THE RIGHT TIME

Our solar system began at a favorable time, after the most violent cosmic fireworks had subsided. In the first 9 billion years of our universe's existence, it experienced the explosions of the most massive stars, the greatest number of galactic collisions,

and the heyday of ***quasars***, galaxies erupting with a trillion times the power of our Sun. By the time our solar system began 4.57 billion years ago, the mayhem had waned, the orbits of most of our galactic neighbors had stabilized, and our universe had greatly expanded, thereby moving many potential hazards far away from us. The Wild West phase of the cosmos was largely over.

Additionally, during the 9 billion years before our solar system existed, generations of stars created and dispersed the heavier elements (all elements other than hydrogen and helium). When our solar system formed, the heavy elements were sufficiently abundant to support life.

IN A SPECIAL SOLAR SYSTEM

The next point may seem odd, but our solar system is also special because it contains only one star. Most stars have partners; they are generally in couples or threesomes. While stable orbits are the rule around a lone star, it is far less likely that a planet will find a stable orbit in a multiple-star system. Without an extremely stable orbit, a planet cannot sustain life.

The Sun also has a favorable mass. If the Sun's mass had been 33% higher, it would have burned out before humans evolved. If the Sun's mass had been 33% lower, the chance of any planet being in the habitable zone of our solar system would have been 4 times smaller.

WITH A BIG BROTHER AND LITTLE SISTER

It's good to have a big brother. Earth is the largest of the rocky terrestrial planets, but it is only a pebble compared with Jupiter. Jupiter has over 300 times Earth's mass and 1000 times its volume. In fact, Jupiter's mass is more than twice the combined masses of all our solar system's other planets. Jupiter patrols the outer solar system, deflecting or consuming many asteroids and comets that might otherwise rain down on the inner solar system, thereby making our neighborhood safer.

It's good to have a little sister as well. Our Moon's mass is 26,000 times less than Jupiter's and about 80 times less than Earth's. Yet the Moon has been very important in Earth's development. The Moon is believed to have formed after a "rock" the size of Mars struck Earth. That rock was another proto-planet like the developing Earth, but 10 times less massive. The rock has been named Theia after the mother of moon goddess Selene, from Greek mythology. Theia's impact is estimated to have occurred 30 to 50 million years after the proto-earth formed (4.5 billion years ago). The collision was cataclysmic. On impact, Theia's kinetic energy was converted to heat and melted the entire Earth from surface to core, allowing iron and other heavy elements to flow down to Earth's center. Because the impact was at a grazing angle, a great deal of material was blasted off into space. Much of it settled into orbit around Earth and eventually accumulated to form the Moon.

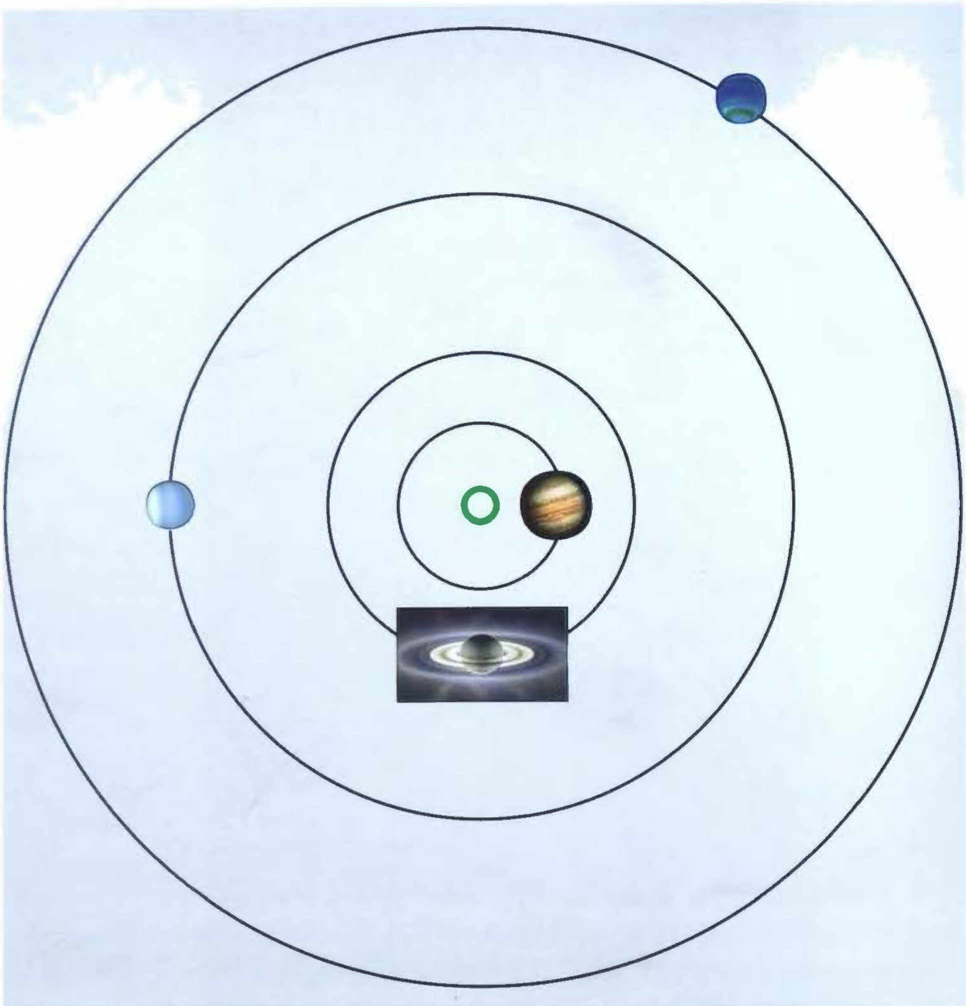

Figure 5.2. Comparison of the orbits of several planets in our Solar System. The largest circle represents the orbit of Neptune. In descending size are the orbits of Uranus, Saturn, and Jupiter. The planets are not to scale, but are greatly enlarged for clarity. The inner green ring represents the entire habitable zone of our Solar System, which is centered on Earth's orbit and occupies only 1/100,000TH of the area of our planetary system. The Solar System is much vaster than shown above, extending to more than one thousand times Neptune's orbit, encompassing the Kuiper Belt and the Oort Cloud, a loose collection of comets and debris.

As a percentage of its host planet, our Moon is by far the largest in the solar system. No other moon has appreciably affected its host planet. But our Moon has had, and continues to have, an important role in Earth's evolution. The Moon creates substantial tides that are believed to have played a role in the development of life in the sea and on land. The Moon also stabilizes Earth's rotational axis, thus providing consistent seasons and giving life a consistent habitat.

THE RIGHT PLANET WITH A PERFECT ORBIT

After Theia's impact, iron concentrated in Earth's core. Heat from the in-fall of the accreting materials that created Earth, as well as radioactive decays, keep much of that iron molten to this day. A molten iron core gives Earth a much larger magnetic field than it would otherwise have, 100 times larger than those of the other terrestrial planets. Our magnetic field protects our atmosphere from the solar wind—the one million tons of charged particles that the Sun spews forth each second. Earth's magnetic field deflects almost all these particles. By comparison, the very weak magnetic field of Mars provides no protection and any atmosphere Mars once had was eroded by the solar wind long ago.

Earth's atmosphere provides an abundant supply of oxygen essential to our survival. The atmosphere also shields us from the most hazardous radiation from the Sun, from cosmic rays, and from the shower of micrometeorites that continually rain down from space at deadly velocities of 25,000 mph and more.

Earth's location in our solar system may be its primary asset. We are in the middle of the habitable zone—close enough to the Sun for water to be above freezing and far enough for it to be below boiling. Taking Neptune as the last planet, now that Pluto has been demoted, the habitable zone occupies less than 1/100,000TH of our entire planetary system, as illustrated in figure 5.2. We are right in the middle of the solar system's Goldilocks Zone.

Having a favorable average orbital radius is not enough. If Earth's orbit were highly elliptical, the oceans might freeze in "winter" and boil in "summer." How elliptical are typical planetary orbits? Excluding Earth and Pluto, the average ellipticity of planetary orbits in our solar system is 7% (with Pluto it would be 9%). This means the average planet's distance from the Sun varies from 7% less to 7% more than average throughout its "year." The amount of sunlight received by the average planet varies from 14% less to 14% more than average. If Earth's orbit were that elliptical, our surface temperature would vary from below freezing to near boiling. Fortunately, Earth's orbit is a more perfect circle, being 4 times less elliptical than our solar system's average.

Finally, Earth's gravity is favorable for life. The gravity of Jupiter-sized planets captures hydrogen and helium, which are by far the most abundant elements in the universe, accounting for 99.8% of all atoms. A planet that is heavy enough to capture hydrogen and helium becomes a ball of gas without a viable solid or liquid surface. Earth is light enough and warm enough that hydrogen and helium gases float to the top of our atmosphere and drift off into space. However, hydrogen atoms that react to form water or other heavier molecules are captured by Earth's gravity. Conversely, a planet that is too light would not capture an atmosphere or retain liquid water. Earth's gravity is strong enough to capture gases heavier than helium and weak enough not to drown in the lighter elements. We are in another Goldilocks Zone in terms of planetary gravity.

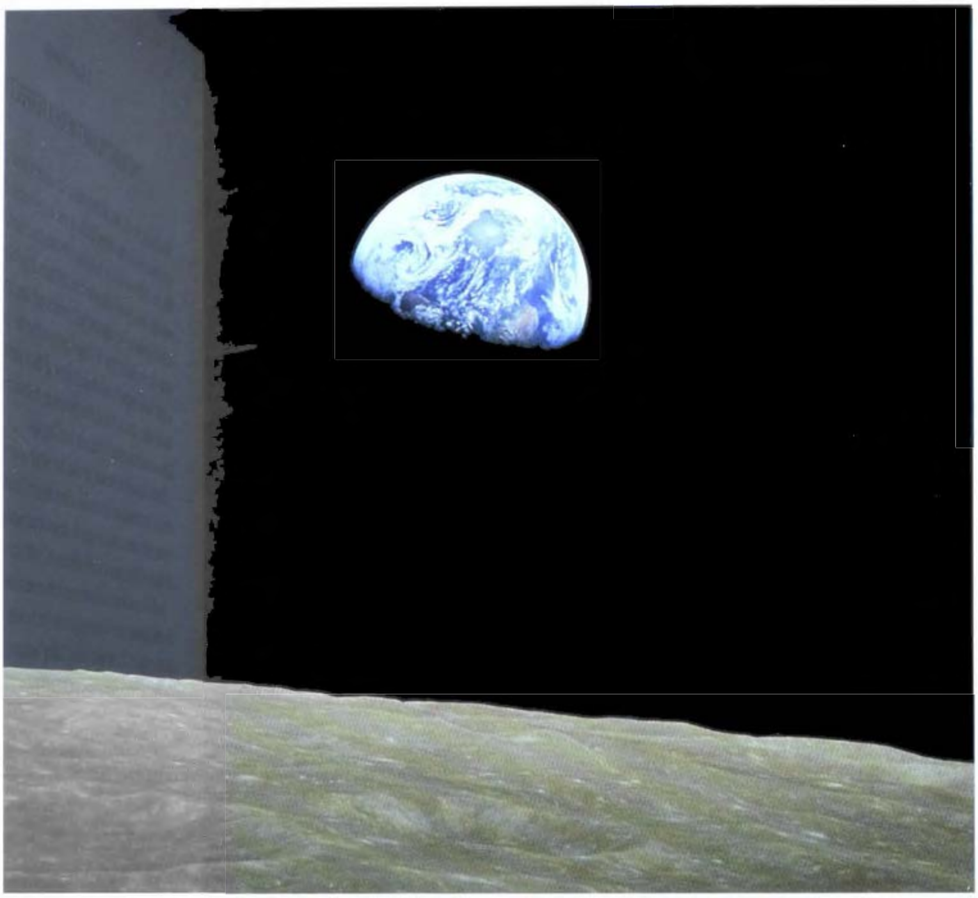

Figure 5.3. Image of Earth rising over the Moon's horizon, taken from lunar orbit on December 24, 1968 by NASA astronauts on Apollo 8.

While there are probably billions of billions of planets in our universe, and there could be many that are habitable, Earth is truly rare and special.

6
The Big Bang

Having learned about atoms, particles, stars, and galaxies, we now have the foundation to discuss science's best theory of the evolution of our universe—the Inflationary Big Bang Theory. The NASA illustration in figure 6.1 illustrates this evolution, from the beginning of everything on the left to today on the right. The most important message of this scientific theory is that our universe did not always exist and that it came into existence in a spectacular flash at a single moment in time. This message has striking similarities to the Book of Genesis.

We will call the beginning of time t=0, and will divide the entire history of the universe into three eras, which in chronological order are: the Era of Quantum Gravity, the Era of Inflation, and the Era of the Big Bang.

We are now in the Era of the Big Bang, the gradual expansion and maturation of the universe. This era began 13.7 billion years ago and continues through the present day. The Big Bang began a millionth of a millionth of a millionth of a millionth of a millionth of a second after the beginning, t=0. Rather than continue to deal with so many millionths, let's call that 1 *tic*; it's much too brief to be a whole "tick-tock." While many detailed questions remain, scientists have high confidence in our understanding of the basic physical laws that underlie the Era of the Big Bang. This confidence is based on our knowledge of particles and on the two great pillars of 20^{TH} century physics: Relativity and Quantum Mechanics. Over the last 100 years, both theories have been extensively tested with extraordinary precision over a very broad range of conditions.

Less certain is the Era of Inflation, beginning one billionth of a *tic* after t=0 and ending at 1 *tic*. This is a period of hyper-rapid expansion. There is a theoretical framework for understanding Inflation, but many details are still in flux.

Most uncertain is the Era of Quantum Gravity, the very beginning of time that spans only the first one billionth of 1 *tic*. Here we know our current physical theories fail. We believe they fail because, in these extreme conditions, space and time are no longer smooth and continuous; thus our normal mathematical tools are not applicable.

One might well ask: "If we understand what happened after the first 1 *tic*, all the way through the next 14 billion years, why bother with that infinitesimal time

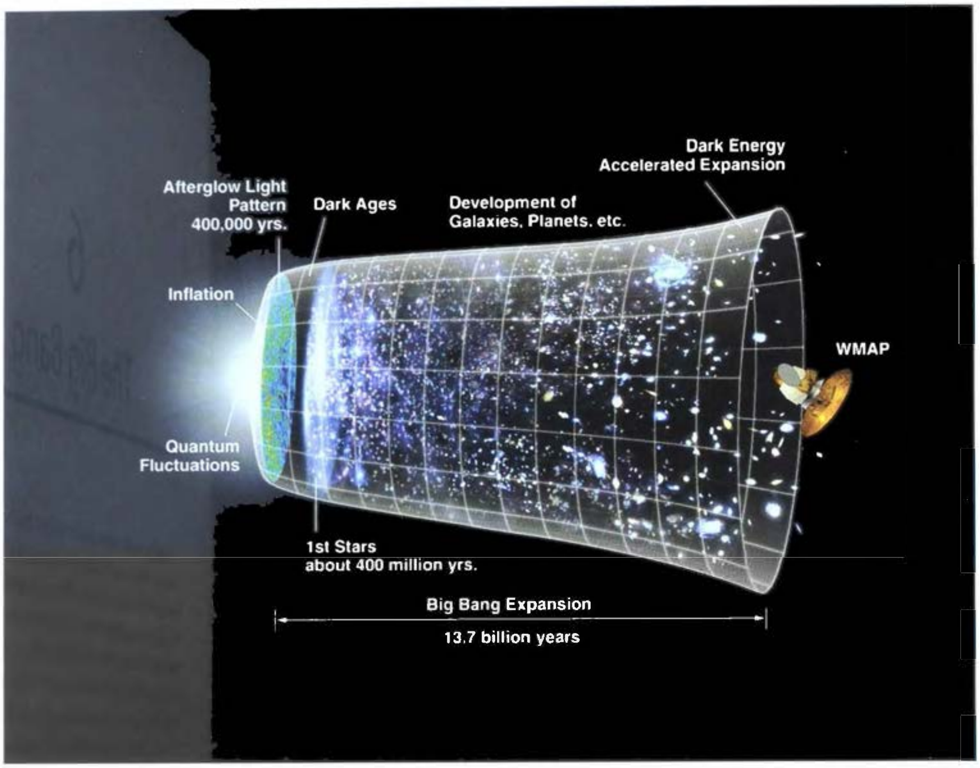

Figure 6.1. NASA illustration highlights the evolution of our universe from the instant the universe came into being 13.7 billion years ago due to "quantum fluctuations" on the left to the present day on the right.

before? Why not just *fuggedaboudit*?" The answer is: it is exactly because we don't understand the first 1 *tic* that makes it so exciting. What gets physicists out of bed in the morning is what we don't know. We are driven to discover nature's secrets. A thousand physicists are devoting their careers to exploring that mysterious, first, tiny 1 *tic*. This is the most important objective of modern physics.

ERA OF QUANTUM GRAVITY

What do we know about the beginning—the Era of Quantum Gravity? From observations by NASA space telescopes, we know with 1% precision that the universe began 13.7 billion years ago as a fantastically small object with a fantastically high temperature. It may have been as small as a millionth of a millionth of a millionth of a millionth of the size of the smallest atom. And its initial temperature was probably over 100 million, million, million, million, million degrees. The universe has been expanding and cooling ever since.

The name Big Bang is something of a misnomer. It was coined by British astrophysicist Sir Fred Hoyle who espoused a competing theory in which the universe

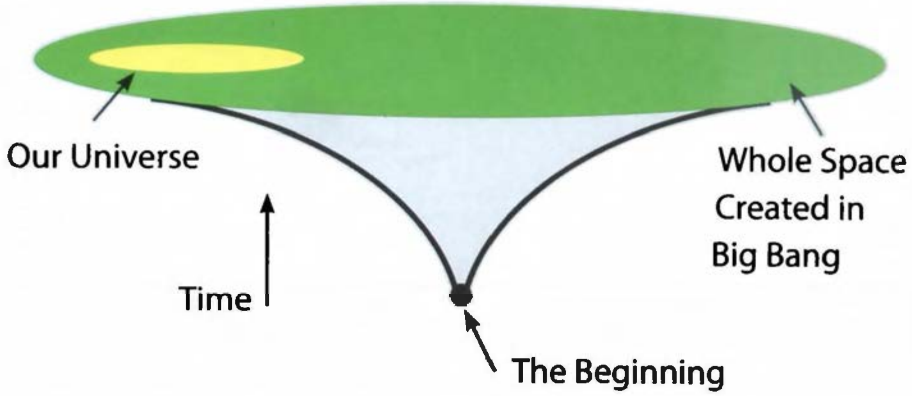

Figure 6.2. During the Era of Inflation, the universe grew spectacularly—more than 10^{30} fold. Here time ranges from t=0 at the bottom to t=1 *tic* at the top. During the next 13.7 billion years, the expansion factor has been "only" 10^{27}.

existed forever, with no beginning and no end. Hoyle may have chosen to denigrate the opposition with a seemingly derisive name. "Big Bang" brings to mind an explosion of matter blasting through a pre-existing space. Actually, there was no pre-existing space or time. The most important aspect of the event at t=0 is that our space and time came into existence. Matter did not explode out into space; space expanded and carried with it everything that existed.

ERA OF INFLATION

By a billionth of 1 *tic*, the universe is large enough and cool enough for space and time to be nearly continuous. Now the Era of Inflation begins. During Inflation, the universe expands by an incredible amount, and at an exponential rate. We believe that during Inflation the universe doubles in size every one millionth of 1 *tic*. In less than 1 *tic*, the universe grows by a factor of more than 10^{30}, perhaps vastly more. This expansion factor is at least 1000 times greater than the expansion factor during the next 14 billion years. As figure 6.2 illustrates, the space created at t=0 probably expands to become vastly larger than our observable universe.

Three very important things happen during the Era of Inflation.

Firstly, the geometry of our universe becomes Euclidean. Any initial curvature of space that may have existed before Inflation is reduced to virtually nothing. We can understand this by considering a small ball, like a ping-pong ball; it is clearly highly curved. Earth is also curved, but normally we don't notice its curvature because Earth is so large. The curvature of any ball decreases with the square of its radius—a ball 10 times larger has 100 times less curvature. The immense expansion during Inflation removes any initial curvature, thereby making the geometry of our universe Euclidean.

Eliminating curvature is essential to creating a livable universe. If, immediately after Inflation, the overall curvature of space were $+10^{-50}$ or more, our universe would have rapidly and completely collapsed in a Big Crunch. If the overall curvature of space were -10^{-50} or less, our universe would have expanded so rapidly that no stars could have formed. Our existence depends on the overall curvature of space at the end of Inflation being virtually zero—differing from zero by no more than ±1 in the 50^{TH} decimal digit! The spectacular expansion during Inflation creates this amazingly precise state.

Secondly, Inflation transforms an infinitesimally small ball, something immensely smaller than a single atom, into our entire universe. It is easy for something small to have a uniform temperature (there's an "almost" coming). Its "pieces" are in such intimate contact that they cannot have different temperatures. Inflation explains why the CMB radiation has so nearly the same temperature everywhere: because at one time, it was all in essentially one place, close enough to share its heat energy.

And thirdly, here's the critical "almost." Quantum Mechanics says that in the microworld of atoms, particles, and the early universe, black and white are replaced by shades of gray. Thus, the temperature throughout our pre-Inflation universe could not be exactly the same, but only "almost" exactly the same everywhere. The temperature and energy density are very slightly higher in some areas and very slightly lower in others—these variations are called ***quantum fluctuations***. As our universe inflates from subatomic to about one foot wide, the quantum fluctuations also inflate and become the variations seen in the CMB in figure 4.10. The regions with slightly higher density become galaxy clusters, and the regions with slightly lower density become great voids in our universe. Without this critical "almost", our entire universe would have the same density everywhere and there would be no stars, no planets, and no us.

During Inflation, space expands far faster than the speed of light. What? Didn't our friend Einstein say nothing can travel faster than the speed of light? Actually, no *thing* can travel faster than light does through empty space. But Relativity allows space itself to expand at any rate at all, even faster than light. As space expands, it carries with it everything it contains.

At the end of 1 *tic*, the exponential growth of the Era of Inflation comes to an end, and the energy which drove that growth is converted into all the particles of nature.

Gravity now dominates quantum effects and the universe evolves according to Einstein's Theory of General Relativity. From analysis of the CMB radiation and other data, we know our universe is homogeneous and Euclidean; its density is nearly uniform and overall space has nearly zero curvature. For these conditions, Einstein's Field Equations of General Relativity have a truly marvelous result—they have only one solution! Sir Isaac Newton's equations have an infinite number of solutions for expanding universes and we could never know which applies to ours. But because Einstein's equations unite space and time with mass and energy, they have only one solution for a homogenous, Euclidean universe. This solution

is called the FRW expansion equation, and considering that this is the equation for the whole universe, it is remarkably simple: $3H^2 = 8\pi e$. Here H is the expansion rate of the universe at any selected time and e is the energy density of the universe at that same time. With the FRW equation and measurements of H and e, we can compute the size of our universe at any time in the future, or at any time in the past back to 1 *tic*. This gives cosmologists a great deal of confidence that they understand the evolution of the universe from 1 *tic* to the present day.

ERA OF THE BIG BANG

The Era of the Big Bang begins at the end of Inflation, and continues to the present day. This is an era of more gradual expansion and maturation. The universe cools as it expands, and matter begins to condense into ever larger assemblies. The structures in our universe start growing at the smallest scales and later proceed to larger and larger scales—the universe grows from the bottom up.

ANTIMATTER ANNIHILATES

At t=1 second, the average temperature of the universe has dropped to a mere 10 billion degrees. This is too cold for new particles and antiparticles to be created. With no continuing source, particles and antiparticles that annihilate are not replaced. Soon, all the antiparticles vanish. Why don't all the particles vanish as well? Almost all of them do, but fortunately, a very small fraction remains.

Generally, nature makes no distinction between matter and antimatter. This leads us to suspect that matter would disappear with the antimatter. If that happened, the universe would be devoid of normal matter and our story would never have begun. However, there is a single exception to nature's even-handedness—a small and otherwise obscure effect that I studied, which treats matter differently from antimatter, and that allows a slight excess of matter to develop during the first one second. As each antiparticle annihilates, it takes a particle of matter with it. When all the antiparticles are gone, the slight excess of matter remains. That slight excess provides all the material from which galaxies, stars, planets, and we are made. The amount by which matter exceeded antimatter was slight indeed. Every one billion antiprotons were outnumbered by one billion and one protons. After all the antimatter annihilated and only the matter remained, our universe contained 10^{89} CMB photons and 10^{80} protons, neutrons, and electrons. And that's all there is today.

How do we know whether it's the matter or the antimatter that nature chooses to favor? How do we know that the Earth and our bodies aren't made of antiprotons, antineutrons, and antielectrons? Maybe we are. However, we are the ones who chose the names of the particles, and we chose to call our stuff matter and call the other stuff antimatter. History is written by the survivors.

SYNTHESIS OF LIGHT ELEMENTS

At t=100 seconds, the temperature is 1 billion degrees. Protons (p) and neutrons (n) are now cool enough to stick together and form the nuclei of the light elements. These include deuterium (whose nucleus has one proton and one neutron: 1p1n), normal helium (2p2n) and its other isotope helium-3 (2p1n), and just a dash of lithium (3p4n). There is not yet any carbon (6p6n) or oxygen (8p8n) in the entire universe. The Inflationary Big Bang theory predicts the abundance of the light nuclei and these predictions match the observed abundances very well, providing another strong confirmation of this theory.

ATOMS FORM AND RELEASE CMB

At t=380,000 years, the first atoms form. The temperature of the universe has dropped all the way down to 5000 ^{O}F, about half the surface temperature of the Sun. Electrons and nuclei are now cold enough to combine and form neutral atoms. The universe is no longer filled with unpaired, charged particles that absorb light—the universe is transformed from the primordial fireball to a transparent gas. No longer trapped within the fireball, the CMB radiation escapes and has been flying through the cosmos ever since. Because these CMB photons have had almost no interactions since the universe became transparent, the images astronomers take today of the CMB, such as figure 4.10, show the universe as it was at t=380,000 years, nearly 13.7 billion years ago.

THE FIRST STARS MAKE THE ATOMS OF LIFE

At t=200 million years, the first stars form. Because the density of matter is still very high, the first stars are particularly massive and short-lived. Within their cores, they produce heavy elements, including carbon, oxygen, and iron. Recall that these elements are produced only in stars. The amounts of carbon and oxygen would be insufficient to support life if not for fortuitous ***resonances*** of these nuclei. Just as strings on a musical instrument have higher frequency harmonics above their base notes, nuclei have higher energy resonances above their normal ***ground states***. The energy of three combining helium nuclei exceeds the ground state energy of carbon, but it exactly matches one of carbon's resonances. This allows the combined nuclei to remain together and "ring" long enough to radiate away the excess energy, leaving behind stable carbon. While this match seems completely accidental, without it the universe would not have enough carbon to support life. Before this carbon resonance was first observed, Sir Fred Hoyle realized theoretically that the universe would be devoid of carbon atoms without it. He predicted its existence and its exact energy. Subsequent experiments found the resonance precisely as he had predicted. A similar situation exists with oxygen, but here the

energy match is not exact. If the match were worse, there would be no oxygen. But if the match were exact, all the carbon would have been converted to oxygen and there would be no carbon atoms to enable life. Both resonances are inexplicably just where they must be for life to exist.

THE SUN AND EARTH FORM

At t=9 billion years, our solar system is born from a collapsing cloud of gas that was enriched with heavy elements by earlier generations of stars. The abundance of these elements suggests our Sun is a third-generation star. The Sun and the ~~nine~~ eight planets form at nearly the same time. Almost all of the collapsing gas cloud, 99.9%, falls into the cloud's center and forms the Sun. The remaining material forms a disk surrounding the Sun that gradually condenses into ever larger bodies, and eventually most of the matter in this disk becomes planets and asteroids.

From here on, we can more precisely determine events retrospectively, thus we will state how many years ago an event occurred, rather than how many years after the Big Bang. Once gaseous materials condense to form solids, their atoms are locked in fixed positions, allowing precise radioisotope dating. Uranium-238, for example, decays to lead-206 with a ***half-life*** of about 4½ billion years. This means that in any chunk of solid material, ½ of the uranium-238 atoms that exist at the start of any 4½ billion year period will decay to lead-206 by the end of that period. After two half-lives, 9 billion years, only ¼ of the original uranium-238 will remain, etc. By combining data from several radioisotopes, including uranium-235 and thorium-232, and comparing regions with different concentrations, the time when a rock solidified can be precisely measured. From such dating, we know that our solar system began forming and the Earth began solidifying 4.57 billion years ago, which is measured with a precision of 1% (±46 million years).

AT LAST, THERE'S LIFE

At about t=10 billion years (3.46 billion years ago), there is evidence of the emergence of life on Earth. This is perhaps only 600 million years after the Earth's surface had cooled enough for life to be possible at all. But amazingly, it took nearly 3 billion years for life on Earth to evolve from single-celled to multi-celled organisms—that transition seems to be more difficult than the emergence of life itself. Multi-cellular animals first developed about 600 million years ago. These were followed by the first fish 500 million years ago, and the first reptiles 300 million years ago. Mammals first appeared 200 million years ago.

Strong evidence exists that a 6-mile-wide asteroid hit the coast of Mexico's Yucatan peninsula about 65 million years ago. The impact was cataclysmic, devastating the global ecosystem, killing the vast majority of all life on Earth, and causing the extinction of perhaps one-third of all existing species, including the

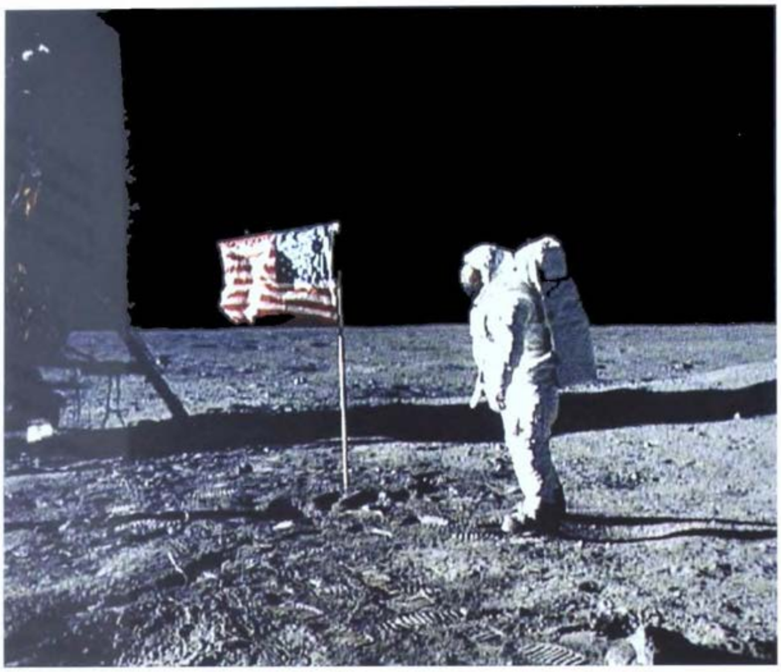

Figure 6.3. Apollo 11 astronauts land on the Moon in 1969. Image by NASA.

then-dominate dinosaurs. Some small mammals survived, and eventually thrived due to the demise of so many ferocious predators.

The first humanoids evolved from primate ancestors about 6 million years ago. Our species, Homo sapiens, originated in Africa 200,000 years ago, and when the last Neanderthals died out 25,000 years ago, modern humans emerged as the last surviving subspecies of our genus.

Finally, after a 13.7-billion-year journey from the beginning of our universe and the beginning of time, here we are today. Figure 6.3 shows one of the feats of which human beings are capable.

The last several chapters have shown how remarkably special is the environment that sustains our life. We live in the Goldilocks Zone of a solar system that is in the Goldilocks Zone of a grand galaxy in a universe with a perfect geometry. We are made of the rarest and finest ingredients that were billions of years in the making. Our atoms are the one in a billion that survived annihilation by antimatter, and one in ten of those that are in stellar systems, and one in 500 of those that are suitable for life, and one in a million of those that are on terrestrial planets.

7
DNA

Scientists are convinced that all forms of life on Earth have a common origin because all life on Earth is based on the same biochemical foundation. All organisms eat, grow, and reproduce using basically the same proteins, made of the same amino acids, under the orchestration of genetic codes written in the same language—DNA, deoxyribonucleic acid. DNA is a complex molecule that encodes not only all the biochemical processes necessary to sustain life, but also encodes the "blueprints" for building every cell in the body and for properly assembling those cells to create the whole living organism. The DNA in every living thing on Earth uses the same code to create proteins—a flower could make every human protein if it were reading our DNA instead of its own.

A model of a DNA segment is shown in figure 7.1, and a chemical diagram is shown in figure 7.2. As figure 7.1 shows, DNA has a double-helix structure composed of two outer strands (illustrated in red, orange, and green) twisting around one another, with vertical bars (shown in gray and purple) connecting the outer strands. Each bar denotes a ***base pair***, a combination of two matching ***nucleotides***; these are the elemental units of DNA. An entire set of DNA is replicated identically in virtually every cell throughout each organism's body.

DNA is huge by molecular standards—a single set of human DNA, from a single cell, could span five feet while being only one ten-millionth of an inch wide. One set of human DNA contains 3.2 billion base pairs and weighs a trillion times as much as a single hydrogen atom. There are as many atoms in one set of our DNA as there are stars in an average galaxy.

About 2% of our DNA is devoted to 22,000 individual ***genes*** that determine how to build the proteins that are essential to all body functions. The other 98% of our DNA was once called "junk" DNA, but we are learning that it too can have a critical role, such as regulating the activity of our genes. Genes vary enormously in length—while they average 3000 base pairs, the gene responsible for muscle protein dystrophin has 2½ million base pairs. Surprisingly, neither the total amount of DNA nor the number of genes is a direct measure of how "advanced" an organism is. The amount of DNA in humans is not radically different from that of many other species that have a large number of body cells.

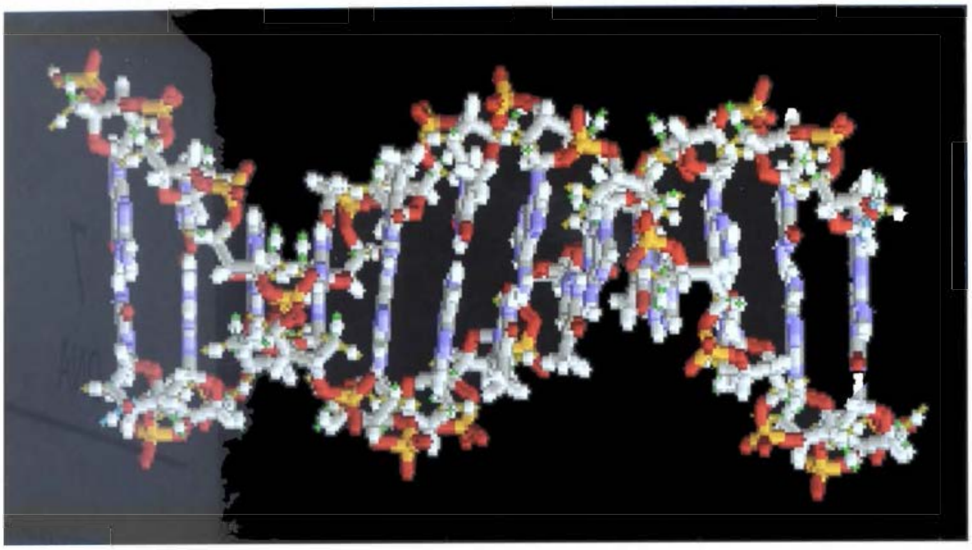

Figure 7.1. Model of a 12-nucleotide-base-pair segment of DNA. The nucleotide base pairs (the vertical gray and purple lines) are similar to rungs on a ladder that connect two spiraling outer strands (red, orange and green) that are the phosphate deoxyribose backbones. Together these form DNA's double helix structure. A single set of human DNA, found in each cell of our bodies, contains 3.2 billion base pairs, would span five feet, and has as many atoms as there are stars in a typical galaxy.

The hepatitis B virus has the shortest DNA we know of at 3200 base pairs, and the DNA of some "nanobes" are not much larger. But these are not self-sustaining organisms; they are parasitic, depending on larger organisms for vital proteins that they cannot produce. Hence they could not have been the first life to arise. The Minimal Genome Project reports that the shortest DNA of any self-sustaining organism currently known has 460,000 base pairs, roughly 1/7000th of human DNA. We will take this as the shortest possible DNA of any original life form, and for convenience, call that the DNA of the "simplest life."

As discussed earlier, the evolution of multi-cellular life from single-celled life took much longer than the evolution of single-celled life from inanimate molecules. This is consistent with the dramatic increase in DNA required for multi-cellular organisms, and seems to imply that the complexity of creating and coordinating an array of organs is far greater than the complexity of the simplest life itself.

Every form of life on Earth has base pairs composed of four types of nucleotides, labeled A, C, G, and T. Thus, all genetic codes on Earth are written in the same four-letter alphabet. Every three base pairs functions as a unit called a ***codon***, which selects one of 20 amino acids in the resulting protein or signals that the protein is complete. Twelve base pairs thus form four codons and encode 21^4, or about 200,000, possible amino acid combinations. Changes in DNA, called ***mutations***, seem to occur randomly at a very low rate; in humans, the mutation rate in protein-coding genes is only one to two base pairs per generation. This is another

area where "junk" and redundant DNA may play a surprisingly important role. If a protein is defined by a gene that occurs only once, a mutation in that gene may very well disable it and prove fatal. But a mutation in an extra copy of that gene or in the "junk" DNA is likely to have very little impact. Thus "junk" and redundant DNA provide an arena for safely "experimenting" with mutations. The eventual accumulation of many mutations may ultimately produce something useful. Since the amount of "junk" is 50 times larger than the protein-coding DNA, the opportunity for developing useful mutations is substantially enhanced.

The amount of information that can be stored in DNA is truly mind-boggling—even the DNA of the simplest life form can encode $10^{203,622}$ possible genetic codes—that's a 1 followed by 203,622 zeros! Let's compare that to the greatest possible number of organisms that could have ever lived on Earth. The most populous forms of life by far are prokaryotes, numbering some $5x10^{30}$. Even if they reproduced every hour for 3 billion years, and even multiplying by 7 for good measure to cover all other forms of life, no more than 10^{45} organisms could ever have lived on Earth—a vastly smaller number than the number of combinations of even the smallest set of DNA.

While stars are immensely larger, DNA has a much more complex and elaborate structure. How did such as an elaborate genetic code come to be?

Evolutionary biologists have often said: "Life comes from life." That may be poetic, but it's not very enlightening. It only means that we understand how life procreates but not how the first life emerged from non-living organic molecules.

Some astrobiologists suggest that the very first life came to Earth on asteroids or comets. Such leftovers from the formation of the solar system continually bombard Earth and may well have brought substantial amounts of water to our planet. We do find organic compounds in both asteroids and comets, and also in interstellar gas clouds. Thus, we know the cosmos naturally produces organic precursors to life. It is conceivable that some elementary form of life emerged out in space and was brought to Earth on an asteroid or comet. Even if true, this would not explain how that life first arose, it would only move the question to outer space.

Back on Earth, Tracey Lincoln and Gerald Joyce published studies in 2009 of small RNA molecules (RNA is a simpler cousin of DNA) composed of several base pairs that self-replicate at the rate of up to one generation per hour. That reproduction rate would have allowed these molecules to quickly dominate the organic "soup" of early Earth's oceans, lakes, and ponds—anywhere liquid water existed. To build up to the complexity of the simplest bacteria, these molecules would have had to grow 100,000 times larger within the 600 million or so years during which life seems to have emerged on Earth.

We can roughly estimate the maximum possible amount of organic "soup" and the maximum frequency of its interactions. Assuming water covered the same area, had the same temperature and percentage of organic carbon then as it does now, and that only the top 30 feet of water contributed (due to the need for sunlight), at most 7 billion tons of organic "soup" could have existed. Even if 100% of that were in RNA molecules containing several base pairs, there could have been

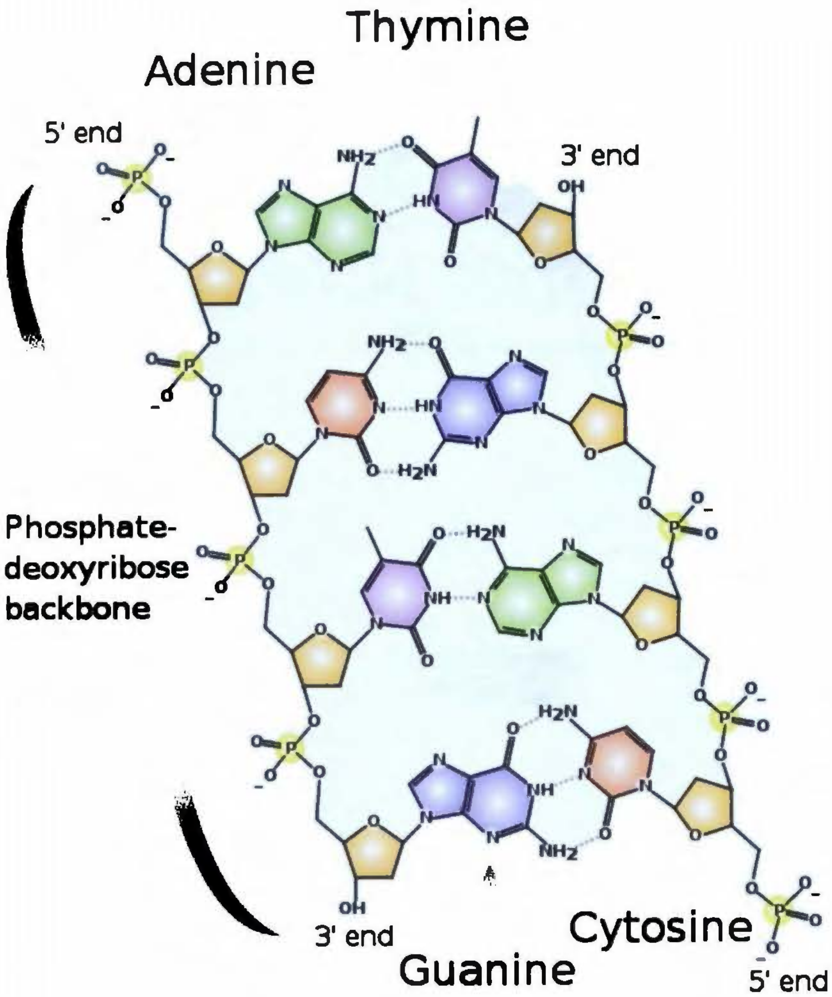

Figure 7.2. Chemical diagram of a 4-base pair segment of deoxyribonucleic acid, DNA. The four nucleotides of DNA are Adenine, Cytosine, Guanine, and Thymine, labeled A, C, G, and T. A is always paired with T, as in the pair at the top of the diagram, and G is always paired with C, as in the pair at the bottom. Thus the code on one side of the helix is the exact compliment of the code on the other side.

no more than 3 trillion, trillion, trillion of them. These molecules could have interacted with one another no more than a million times per second, due to the time required to span the distance between them. Thus there were at most 15 trillion interactions per molecule per year, with each being an opportunity to grow more complex.

As big as these numbers are, is all this enough to randomly create life?

8
Extreme Numbers

Before exploring the odds that life's requirements occurred accidentally, we must deal with, dare I say it, numbers. Questions that start "how likely is ...?" must be answered with numbers—sorry, but that's life. Since the random occurrence of each of these requirements is very unlikely, the numbers we will need to use are much smaller than most of us are accustomed to. One way to translate these extreme numbers into something more familiar is to use a deck of 52 playing cards, of which one is the ace of spades, A♠. The odds of drawing the A♠ from a properly shuffled deck are 1 in 52, since all 52 cards are equally likely. Drawing the A♠ is a long shot. What about drawing it twice in a row? Imagine drawing one card from each of two shuffled decks. How likely is it that both cards are the A♠? The odds are 1 in 2704 (52 times 52), much more unlikely than drawing the A♠ only once. The odds of drawing the A♠ three times in a row are 1 in 140,608; four times are 1 in 7.3 million; five times are 1 in 380 million; six times are 1 in 20 billion. You get the idea—each time we add another draw, the odds become much more unlikely.

Note that doubling the number of aces doesn't just make the odds half as likely, it reduces the odds drastically.

Computing the odds of accidental life is made easier using Piccioni's Theory of SIN, Semi-Infinite Numbers that is, which I am publishing here for the first time. The key idea is that when numbers get extremely large, we can, for all practical purposes, ignore much smaller numbers, as my theory specifies. If you find this mathematical discussion too tedious, feel free to skip on to the next chapter.

I claim that for some very large number X there is no practical difference between X and X+1. For example, imagine I offered you a choice between two piles of $1 bills and said that one pile was worth $1000 and the other $1001, but didn't say which was which. Would you count the piles, or just grab one before I changed my mind? We can write 1000 as 10^3 (the "3" counts the number of zeros). Perhaps you would count the piles at 10^3 bills. What about one million (10^6)? Or one billion (10^9)? I claim every reasonable person would stop counting if X, the number of bills, were large enough. Thus, X may be determined by our indifference (X and X+1 are "about the same"). X may also be determined by our imprecision; in many situations we may not be able to measure the difference between X and X+1.

If you think that in counting a thousand $1 bills you might be off by a few bucks, then why bother counting?

Figure 8.1. A normal deck has 52 cards. The odds of drawing the A♠ from a shuffled deck are 1 in 52.

Where is all this going? Consider an example. Earlier I said our universe contains 10^{89} CMB photons that have existed since before the first stars. We know stars emit a lot of light and that the universe contains 10^{22} stars, so shouldn't we add the photons emitted by stars to get the total number of photons today? There's no need. The Sun emits 5×10^{45} photons per second, and stars have been burning for 13 billion years, or 4×10^{17} seconds. Multiply all those: 10^{22} times 5×10^{45} times $4 \times 10^{17} = 2 \times 10^{85}$, certainly a very large number—it has 85 zeros. But $10^{89} + 2 \times 10^{85} = 10^{89.0001}$. I claim that reasonable people would agree that 89.0001 is the same as 89 for all practical purposes. (My theory says we can ignore such small differences even in an exponent.) For the purpose of counting photons, all the photons emitted by all the stars for the entire life of the universe are insignificant compared to the vastly more numerous CMB photons.

Another example: we will later deal with even larger numbers such as $10^{200,000}$. That number multiplied by one trillion (10^{12}) is $10^{200,012}$. Incredible as it may seem, I claim that for numbers this immense, multiplying by or dividing by one trillion doesn't make a significant difference.

To make this less abstract, consider the train tracks in Figure 8.2. At the bottom of the image, the rails are separated by the normal gauge, 56½ inches. (That odd number originated with Roman chariots and has come down to us unchanged through the ages.) Due to perspective, the rails seem to converge at a "vanishing point", point V, near the top of the image. At some point in the distance, call it point A, the rails appear a thousand times closer than normal gauge (point A isn't shown as it's so close to V). A thousand times farther from us than point A, the rails appear a million times closer than normal, call that point B. Even though a thousand and a million are quite different, points A and B are virtually indistinguishable from our perspective. In fact, in this image, points A and B are both within a millionth of an inch of V, a point that is infinitely far away.

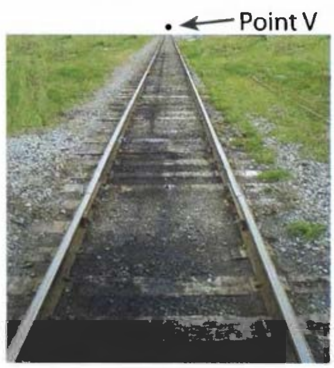

Figure 8.2. Converging railroad tracks are an example of perspective. Point V is the vanishing point, infinitely far away.

Thus, with extreme numbers, we only have to compute the most extreme ones—all smaller numbers can be safely ignored. This will greatly simplify our estimates.

9
Odds of Accidental Life

Up to this point, we have considered life's requirements in these categories:

What are the atoms that life requires?

What are the requirements for a viable universe?

What planetary habitat does life require?

What are life's requirements for a genetic code?

Let's now summarize what has been discussed in the prior chapters, and estimate, as well as possible, the odds that these requirements could be satisfied by random chance.

THE RIGHT ATOMS

What are the odds of having the right atoms. Of all the particles that existed in the beginning, all but one in a billion were annihilated by antiparticles. Of the survivors, only one in 500 were converted into carbon, oxygen, and other elements necessary for life. Of those, only one in ten million were gathered by stars and ended up on terrestrial planets. Overall, the odds of a particle becoming life-sustaining are the same as drawing the A♠ 11 times in a row (see chapter 8). We are indeed made of rare and precious ingredients.

A VIABLE UNIVERSE

A viable universe must be stable—it must not immediately collapse or explode—and it must contain stars, planets, and atoms. Half a century ago, Einstein wondered about this as well; he said: "What really interests me is whether God had any choices in the creation of the universe." I believe his quandary was: must the universe be the way it is due to the laws of physics and math, or could it have been very different? Now fifty years later, we believe there are about 20 choices—20 "knobs" that could be adjusted, like the knobs on an oven for temperature, cooking time, etc. A universe could exist, according to the laws of physics and math, for

almost any setting of those 20 knobs. However, it seems that life is possible only if all the settings are very close to the settings in our universe. For example, one knob is the mass of the proton, an essential part of all atoms. If the proton's mass were just ¼ of 1% heavier or just ¼ of 1% lighter there might well be no life. The odds of protons having the right mass may be less than the odds of drawing the A♠ twice—slim, but not too bad. Another knob is the universe's initial curvature, which could have any value from -1 to +1. But life is possible only if this value is very close to 0; in fact, it must not differ from 0 by more than 1 in the 50^{TH} decimal digit. The odds of that are the same as the odds of drawing the A♠ 29 times in a row—I wouldn't bet on it. The universe has 18 more knobs that must be just right, each further reducing the probability of supporting life. Overall, the odds of a viable universe are probably less than drawing the A♠ 40 times in a row.

Clearly, of all possible universes, ours is extremely rare and wonderful.

CAN ATOMS AND UNIVERSES EVOLVE?

Is it possible for a viable universe with the right atoms to "develop" over time? A leading cosmologist, Lee Smolin, says it can, and calls his theory Cosmological Natural Selection. While there is no definitive evidence for Smolin's theory, it is a very innovative idea. I hope it is true because it envisions viable universes continuing forever, and presumably life continuing as well. Smolin suggests that when matter collapses into a black hole, it doesn't remain lifeless for all eternity. He says it might explode out "the other side" into a new space and time, and create a new universe that is something like a child of the original universe. Recall that the settings of 20 "knobs" define the characteristics of a universe. Perhaps, he says, the knob settings of the child universes are almost the same as their parent's, but with some slight changes (mutations). If all that were true, then universes that produce the most black holes would have the most offspring. Knob settings would evolve over time to maximize reproductive success (to make the most black holes) and part of that success would be producing stars and producing carbon, oxygen and other heavy elements that help gas clouds collapse to form stars. Over many generations of universes, the knob settings of the surviving universes would become tuned to just the right values. The fact that we exist in a universe with the "right stuff" would then be no more surprising than the fact that we are born with precisely tuned DNA.

A HABITABLE PLANET

Earth is a wonderful and extraordinarily improbable habitat, as discussed in chapter 5. We are in the right place in a favorable galaxy. Our Solar System formed at the right time, with only a single star that has just the right mass. Earth is protected by a big brother, Jupiter, and our seasons are consistent due to a little sister, our

Moon. Earth has a nearly circular orbit of just the right size, as illustrated in figure 5.2. It has a magnetic field that protects our atmosphere, and has the right mass to support life. What are the odds of all that? No one knows for sure, but Earth may be one in a billion, more rare than drawing the A♠ 5 times in a row.

We live on an extremely rare and wonderful planet. If Earth is one in a billion, our galaxy might contain only several hundred other equally good planets. If so, the nearest may be several thousand light-years away. Even with the fastest rocket we have ever built, it could take 80 million years to travel that far. (imagine how many times you'd hear "Are we there yet?") As Paul Dimotakis, Chief Technologist of JPL, the NASA/Caltech Jet Propulsion Laboratory, said: "Good planets are hard to find. We need to take good care of this one."

AN EFFECTIVE GENETIC CODE

Finally, what about life itself? For DNA base pairs to randomly assemble into anything remotely resembling complex, multi-cellular life is completely out of the question. For example, randomly arranging 3.2 billion base pairs and creating a human being is less likely than drawing the A♠ one billion times in a row. What about something less ambitious? Randomly replicating the single human gene for dystrophin, the largest of our 22,000 genes, is less likely than drawing the A♠ 600,000 times in a row. Randomly replicating the DNA of the simplest known life is about as likely as drawing the A♠ 119,000 times in a row.

None of these odds is even remotely possible—none of these specific genetic codes could possibly have arisen from scratch by pure chance. Our universe simply is not big enough or old enough to expect any such extraordinarily unlikely events to have occurred. How can we be so sure? Let's consider the most optimistic scenario imaginable. Assume all the carbon atoms in the universe were converted into nucleotide base pairs, assume all the other atoms that DNA requires were readily available, and assume all those base pairs interacted with one another a billion times per second from the beginning of time through today (nearly 14 billion years). Clearly, these assumptions vastly overestimate both the number of nucleotides and the number of their interactions. Yet, even in this most optimistic scenario, all those interactions are likely to produce only one molecule as long as 230 base pairs (an event as improbable in any single interaction as drawing the A♠ 59 times in a row). We could expect only one such molecule to arise in only one location in the entire universe and at only one moment since the beginning of time. Even in this most extravagantly optimistic scenario, random chance could have delivered only 1/2000$^{\text{TH}}$ of the DNA of the simplest known life. To expect a single molecule with 238 base pairs—only 8 more—we would have to wait another 27 trillion years; this is illustrated in figure 9.1. The amount of time required to randomly replicate the simplest DNA (to fill the entire green box in this figure) is $10^{203,530}$ years—that's a 1 followed by 203,530 zeros—vastly beyond the estimated lifetime of the universe and vastly beyond any semblance of reality.

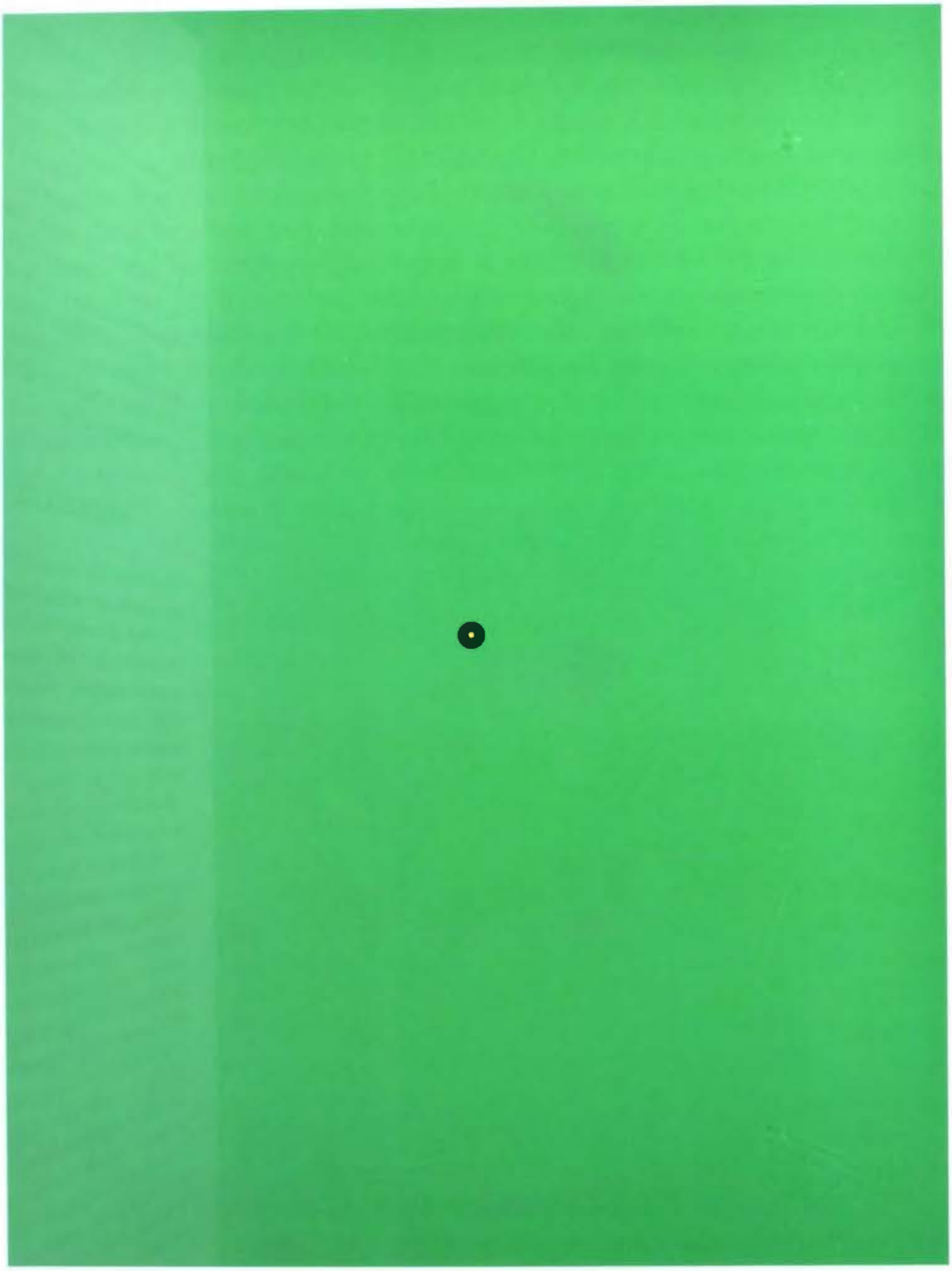

Figure 9.1. Comparison of amounts of DNA. The green box represents the smallest DNA of any known form of life. The small black donut represents the longest DNA that could have arisen by random chance just once, at any one point in the entire expanse of our universe and at any one moment in its entire history; it is only 1/2000TH of the green box. Even if the universe were 2000 times older (27 trillion years), the black area would still not fill the green box, because the relationship is exponential. In 27 trillion years, all that would be added to the randomly created DNA would be the tiny yellow dot filling the donut hole. It's so small, I hope you can see it.

Can science explain how life might arise by random chance despite these staggering odds? No—at least not yet. But two ideas are worth mentioning.

Implicit in our analysis so far is the assumption that viable genetic codes are quite rare, and thus almost every possible DNA (or RNA) combination must be explored to find any form of life. For example, if the number of viable genetic codes is similar to the maximum number of organisms that could ever have lived on Earth (see chapter 7), the odds of randomly producing any form of life would be like drawing the A♠ 118,966 times in a row—imperceptibly different from the 119,000 times in a row for a single specific genome.

Our first idea to overcome these staggering odds is that perhaps viable genetic codes are relatively common. For life on Earth to have arisen by chance within 600 million years, given the number of interactions computed in chapter 7, the odds of a single interaction producing life would have to be no worse than drawing the A♠ 34 times in a row. Of the $10^{203,622}$ possible genetic codes of the simplest DNA, at least $10^{203,564}$ would have to produce some form of life. But if more than $10^{203,568}$ combinations produced life, there should be ample evidence for the spontaneous appearance of many entirely new species; yet such evidence doesn't exist. While this idea is mathematically possible, there is also no evidence that viable genetic codes are sufficiently common, and the required numerical matching of these unrelated values would be the most spectacular coincidence known to science.

Our second idea to overcome the odds against accidental life is that effective genetic codes could arise through a step-by-step process. As we discussed in chapter 7, some small RNA molecules can self-replicate. To give rise to the first, simple life form on Earth, these molecules would have had to grow 100,000 times larger within about 600 million years. This could have been possible if RNA had evolved through 4000 intermediate steps. Each step must have been stable, self-sustaining, and self-replicating, and must have added 116 base pairs in a span of 150,000 years. Each intermediate step would be as unlikely as drawing the A♠ 30 times in a row, but that is feasible considering the number of RNA interactions computed in chapter 7. More intermediate steps would make each step easier, but each step must be stable, self-sustaining, and self-replicating. This idea is intriguing but incomplete and not truly satisfying due to the ad-hoc assumptions and the total lack of evidence for any intermediate steps. If natural processes produce stable, self-sustaining, and self-replicating RNA or DNA molecules of intermediate lengths, such as 1000 base pairs, then every bucket of ocean water should be full of them. But none have been discovered in nature nor have any been created in our labs.

The enormous difficulty in achieving a viable genetic code adds one more twist to our story of life—our biochemistry may be the only one that exists anywhere. An alternative biochemistry might utilize some different amino acids, different proteins, different nucleotides, or a structure other than our double-helix. But if that biochemistry were less efficient (required more genetic material) by even $1/100^{TH}$ of 1%, the time required to assemble its genetic code would be 100 billion, billion times longer than ours, so much longer that it would never happen. It seems only the very most efficient genetic code has any chance at all.

CONCLUSION

Life requires a suitable habitat. We have found that our universe is precisely tuned with the right geometry, the right atoms and particles, the right stars and planets to provide this habitat. Science has some ideas about how such extraordinarily precise tuning may have evolved naturally, but we lack any definitive confirming evidence.

Life also requires some form of genetic code. At this time, science has no convincing explanation for how a viable genetic code could have emerged by random chance through any known physical or chemical process.

Science will continue to advance—as it always does. One day we might discover how life ***could*** have emerged through an entirely natural mechanism. But, even that would not prove that's the way life ***did*** emerge.

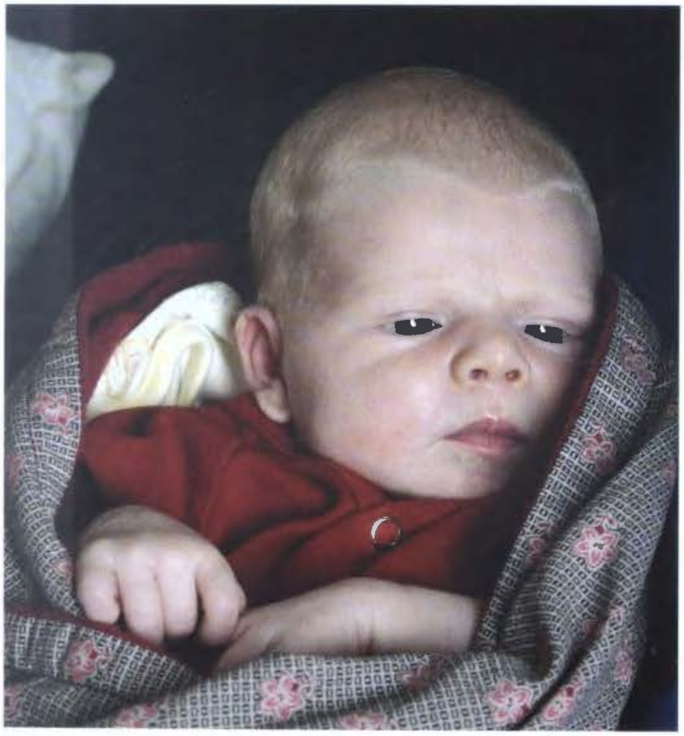

Figure 9.2. Author's three-week-old granddaughter Ashley Renee.

We end where we began,
with our fundamental question:

Can life be merely an accident?

What do ***you*** think?

Index and Glossary